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MANAGING FUEL QUALITY IN THE
DEPARTMENT OF DEFENSE

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Robert W. Salthouse
Marshall Hoyler

LOGISTICS MANAGEMENT INSTITUTE
6400 Goldsboro Road
Bethesda, Maryland 20817-5886

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Fuel quality problems can have serious consequences on DoD's mission. Poor quality fuel can degrade weapons systems performance and damage critical weapons components. Avoiding such problems is the responsibility of DoD fuel managers.

We find that current quality control procedures detect and avoid almost all fuel quality problems before the fuel is used. DoD has experienced relatively few documented fuel quality problems that cause inadequate performance of DoD weapons systems.

Of the few fuel quality problems that exist, the most common is diesel fuel deterioration during long-term storage. War reserve stocks in remote overseas locations, particularly those with hot climates, are most susceptible. The rapid turnover of diesel fuel stocks generally avoids deterioration in the United States.

Strategies to improve fuel quality management should, therefore, focus on diesel fuels in long-term storage. We recommend that the Defense Logistics Agency:

• Buy less-severely processed and, thus, more stable diesel fuels for war reserves in remote locations where immediate availability is critical.

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- In hot climates, construct underground storage facilities to reduce fuel temperatures and improve fuel stability, unless the cost is prohibitive.

- Continue efforts to increase the turnover of fuel stocks in remote locations by contracting with commercial firms to store and sell military specification fuels in lieu of their regular fuels.

- Continue its recently revised policy of testing fuels in long-term storage every 3 months in the Middle East and every 6 months elsewhere.

For a more lasting solution to diesel fuel deterioration, we recommend that the Service fuels research offices continue to investigate the use of additives for increasing stability. The research offices should also develop a new, more reliable diesel fuel stability test. The current test is ineffective in screening fuels likely to deteriorate.

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Executive Summary

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CONTENTS

CONTENTS (Continued)

TABLES

FIGURES

CHAPTER 1

FINDINGS, CONCLUSIONS, AND RECOMMENDATIONS

Are new policies or actions needed to minimize the risks to military readiness associated with changes in petroleum fuel quality? This chapter presents our findings, conclusions, and recommendations. Chapters 2 through 5 and Appendices A through D provide supporting detail.

FINDINGS AND CONCLUSIONS

DoD has experienced a number of fuel-related problems, including fuel deterioration during storage, vehicle filter plugging, excessive filtration times which reduce the efficiency of fuel-pumping equipment, and low jet fuel "lubricity" which shortens fuel pump life. When such problems occur, they can have serious consequences, even shutting down entire facilities for a time.

Extent of Problems

Despite the occasional severity of DoD's fuel quality problems, available evidence suggests that they affect only a very small amount of the fuel that DoD annually purchases, stores, and uses. Most DoD fuel problems are not chronic; as new and different types of fuel problems have appeared, DoD's fuels experts have found ways to deal with them. Finally, current trends do not provide a basis for reliably predicting the future quality of petroleum fuels. By continuing to use current procedures and expertise, DoD should remain capable of managing most of the fuel quality problems that it faces in the forseeable future.

Analysis of time-series data shows that very few jet fuel properties deteriorated during the late 1970s and early 1980s; the overwhelming majority of properties measured either stayed the same or improved. Moreover, the jet fuel properties that deteriorated generally showed only slight declines, and the fuels remained well within specification. Diesel fuel properties have exhibited more deteriorations than improvements although on average, they also remained well within specification.

Available data on problems experienced by units in the field suggest that DoD has not experienced a large number of quality problems during fuel storage and use. The Defense Logistics Agency (DLA) has experienced relatively few quality problems recently, despite the fact that it maintains DoD's largest fuel inventory. The Army, which maintains the most systematic data, has documented only 30 problems in the period 1980 through 1985. Neither the Navy nor the Air Force has reported very many recent problems.

While some fuel problems may not be reported to higher levels, we find two reasons to doubt the occurrence of large-scale underreporting. First, DLA subjects the fuels that it transports and stores to thorough and repetitive testing, which makes it unlikely that serious bulk fuel quality problems could exist and remain unreported. Second, underreporting also seems implausible in light of DoD incentives. Fuel personnel in the Military Departments can (and should) reject fuel shipments from DLA on suspicion that the fuel may lead to poor equipment performance.

Not all fuels pass through DLA's thorough screening mechanisms, however. In particular, most Army ground fuels (gasoline and diesel fuel) are delivered directly to Army installations by commercial suppliers. Since the large number of such installations makes rigorous screening difficult, some Army ground fuel problems may go unreported. The Army tests selected fuel samples after acceptance; in 1986, about 15 percent of diesel fuel samples failed to meet one or more specification limits. The Army screens its tactical fuels more carefully but currently judges that testing of all fuel deliveries at all installations is not cost-effective.

Effects of Crude Oil Quality and Refining

We examined evidence on crude oil quality and changes in refinery operations to determine the causes of changes in product quality and the possible direction of future fuel quality trends. Crude oils refined in the United States declined in quality during a recent 8-year period — they became heavier and the sulfur content increased. We find no evidence that crude quality is worsening worldwide, however. In general, the U.S. crude oil quality decline has had limited direct effects on product quality. The main effect of heavier crude oil is to increase the need for refinery conversion processes that convert heavy products into lighter, more valuable products. In fact, imported crude oils probably became heavier as a direct result of a

simultaneous growth in conversion capacity. More conversion capacity gave U.S. refiners the ability to increase their purchases of lower quality crude oils, which are cheaper than the light, low sulfur crude oils that "simple" refineries are forced to use.

It is true that increased reliance on conversion processes in refining tends to reduce product quality. However, domestic conversion capacity has grown slowly since 1970. More important, the overall utilization (or "severity" of operations) of conversion capacity has not changed significantly during the past 15 years. Within that overall trend, however, domestic refiners have increasingly relied on coking processes for conversion, and those processes can have a more detrimental effect on fuel quality than other, less severe processes. Available evidence on planned U.S. refinery construction gives no basis for expecting a sharp increase in domestic conversion capacity over the next few years. The degree to which that capacity will be used in the future depends on the marginal economics of refinery operations. If, as appears to be the case, the quality of imported crude oil declined as the result of growth in conversion capacity, then the slowdown in conversion capacity growth should also lessen the crude oil quality decline.

Effect of Long-Term Fuel Storage

While DoD appears to have relatively few fuel problems, it's fuel logistics system has experienced problems and may continue to experience them as diesel fuel deteriorates during storage. Unlike commercial firms, DoD's mission requires that it store fuels for long periods in certain locations. Storage problems may have resulted from intensive refining processes and/or storage and handling practices, but neither such refining nor prolonged storage inevitably implies instability problems.

The fact that DoD has to store fuels for long periods has prompted a search for an administratively feasible test that can reliably predict fuel instability. Unfortunately, no such test currently exists. One reliable test for predicting instability requires a prohibitively long time (13 weeks) to administer. Another test — DoD's accelerated stability test for diesel fuel — does not reliably predict storage instability. DoD fuels researchers are searching for a more reliable test.

Other nations have successfully stored fuels for extended periods (10 or more years) by storing only less severely-processed fuels, testing stored fuels regularly,

and using underground storage to lower fuel temperature. Those nations include Israel, Switzerland, Sweden, Norway, and South Africa.

RECOMMENDATIONS

Our recommendations concentrate on the bulk petroleum mobility fuels that DLA transports and stores and that account for most of the fuel used by the Military Departments. We do not make any recommendations directly aimed at improving Army diesel fuel quality because we have no evidence to indicate a large number of end-user fuel problems. (Specification failures do not constitute fuel problems unless they demonstrably reduce weapons system performance.)

The Army could reduce the number of diesel fuel specification failures by instituting more thorough acceptance procedures and could also increase diesel fuel quality for end users by installing more filter separators. Available evidence, however, does not indicate that the Army is incurring high costs from poor quality fuels. The Army would have to establish that its fuel problems are significantly underreported in order to show that improvements would be cost-effective.

Service Testing and Research

We recommend that the Service fuels research offices continue their efforts to develop a more reliable diesel fuel stability test. DoD's current diesel fuel stability test – American Society for Testing and Materials (ASTM) D 2274 – was designed to serve the logistics system by rejecting diesel fuels with the potential to deteriorate during long-term, or dormant, storage. Experience and research findings both clearly show that the test fails to screen out such potentially unstable fuels; despite the test, DoD has received fuels that have deteriorated during storage.

In addition, we recommend that the Services continue to examine commercial stability additives for possible inclusion in diesel fuels intended for long-term storage, although such measures may not be needed for high-turnover diesel fuels. Until researchers develop a more effective screening test and/or reliable stability additives, DoD logisticians must rely on other methods to ensure the reliability of DoD diesel fuels during prolonged storage.

DLA Testing Policy

We recommend that DLA continue its recently revised policy of requiring that dormant stocks be tested at least every 6 months worldwide and every 3 months in the Middle East. The Swiss, for example, only test their fuels every 2 to 3 years; unlike the Swiss stocks, however, DoD distillate fuels are not limited to straight-run (less-severely processed) material and they are stored in a variety of storage tanks, many above ground, in scattered locations. Thus, DoD stocks have a greater potential for deterioration. Finally, experience shows that a fuel stored in isolation can depart significantly from specification within 6 months. The aim of the testing program should be to detect such fuels and correct them by filtering, blending, or other appropriate methods.

With it's policy of frequent testing, DLA should be able to identify problem fuels in time to correct any instability problems. Early identification also means that DLA will have to select the least costly way of correcting any particular problems. It is clear that the least-cost alternative is immediate use of the problem fuel before further deterioration can occur. However, the costs associated with doing so vary. If the fuel can be used as is, the costs are those of moving it to the user and replacing it. If blending is required, the cost includes transporting the problem fuel from its storage location to a busy fuel depot for blending and transporting replacement fuel to the storage location. Finally, if DLA downgrades the problem fuel to a less stringent use or sells it on the commercial market, costs would normally include some transportation plus a quality discount. (For the latter alternative, procedural changes may also be required; we know of no instance in which DLA has disposed of fuel commercially.)

DLA Fuel Storage Strategies

Contractor Storage and Disposition

We also recommend that DLA continue its study of the feasibility of contracting with overseas petroleum firms to store military specification fuels in place of their normal commercial stocks at their fuel depots in order to ensure the reliability of diesel fuel that must be stored for long periods of time. Under that strategy, DoD would pay the quality premium between the military and commercial

fuel prices, and in return, commercial firms would turn the fuel over frequently enough to avoid storage stability problems.

While we support DLA's commercial storage initiative, we recommend that it compare the advantages of commercial storage with those of the current test-and-correct policy and with two alternative strategies for increasing the reliability of fuels in long-term storage. The two alternative strategies are described below; both have been successfully used by other nations.

Straight-Run Fuel Purchases

One alternative strategy involves the purchase of less-severely processed straight-run fuels for long-term storage. DoD could adopt a separate specification for those diesel fuels destined for long-term storage. The only change from current specifications would be the addition of a requirement limiting the fuel to straight-run (and possibly hydrocracked) material, following the example of Israel and Switzerland. The two distillate specifications would appear identical to end users since the differences would only be important within the logistics system. A separate specification would probably require changes in DLA's acquisition procedures because fuels are currently solicited with no specific storage location in mind, apart from a general geographic area.

For some fuels, DoD has, in effect, already implemented such a policy. Jet fuels currently have a maximum olefin content of 5 percent, which essentially guarantees only straight-run (or hydrocracked) fuel. The Marine Corps has achieved the same result as a straight-run specification by using JP-5 (Navy jet fuel) in lieu of diesel fuel for in-vehicle fuel storage aboard pre-positioned ships.[1] Using JP-5 as a standard fuel in the Middle East would achieve essentially the same result since JP-5 can be used by Naval vessels as well as most military ground vehicles instead of diesel fuel. (JP-8 – the European standard jet/diesel fuel – is unacceptable to the Navy because of its low flash point.)

A straight-run limitation would decrease but not absolutely eliminate stability problems. Despite the 5 percent restriction on olefin content mentioned above, for example, DLA has reported some instability problems with jet fuels. Testing, and

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[1]This procedure was recommended by the U.S. Army Belvoir Research, Development and Engineering Center, Fort Belvoir, Virginia.

occasional blending and filtering, will still be necessary. In addition, any tightening of a specification generally costs money. A straight-run limitation, even if only imposed on the relatively small volumes of fuels destined for long-term storage, would incur costs and might limit the volume of fuel available for those particular regions.

Underground Storage

The second alternative strategy involves using underground storage tanks for dormant stocks wherever possible, particularly when storing essential replacement strategic fuel stocks in remote locations. DoD routinely seeks to lease underground storage; however, above-ground storage is typically the only kind available. For that reason, we suggest that DLA consider extraordinary measures (e.g., subsidized construction) that could make underground storage available where none currently exists. We recommend that DLA compare the feasibility, cost, and effectiveness of such measures against the same attributes of alternative strategies such as testing and replacement. That comparison should explicitly consider two advantages of underground storage: the high transportation cost associated with shipping to remote locations and, more important, the expected cost associated with the long time required to replace bad fuel in an emergency.

Quality Control

Finally, we recommend that DoD continue to devote adequate resources to fuel quality control if it wishes to maintain a high level of fuel quality in the future. Petroleum fuel quality cannot be guaranteed by specifications alone. DoD has achieved a relatively low number of fuel quality problems only by maintaining a high level of quality control throughout its fuels logistics system. Both DLA and the Military Departments should maintain a level of technical expertise sufficient to enable them to solve unique fuel quality problems as they appear and to ensure that DoD fuels specifications keep pace with equipment requirements. DoD also needs to ensure that changing equipment requirements do not outstrip the ability of available fuels to meet those requirements.

CHAPTER 2

FUEL QUALITY, REFINING, AND SPECIFICATIONS

THE NATURE OF FUEL QUALITY

The quality of the petroleum fuels used by DoD weapons systems is an essential element of DoD logistics. Petroleum fuels power most of DoD's mobile weapons systems, are relied upon to produce optimum equipment performance under adverse circumstances, and must remain reliable even after relatively prolonged storage.

We define fuel quality as the degree to which a particular batch of fuel produces adequate engine performance and satisfies other important criteria, such as safety in handling and adequate storage life. Although fuel quality is normally measured by testing the fuel for adherence to specifications, the ultimate measure of quality is engine performance.

Fuel quality depends upon three primary factors: engine requirements, types of crude oils and refining processes, and fuel handling and storage procedures. Quality, obviously, cannot be defined independently of engine requirements; turbine engines in jet aircraft require different types of fuel than internal combustion engines in trucks.[1] Moreover, newly developed engines that demand increasing performance of traditional fuels may cause a relative decline in fuel quality even when fuel chemistry remains unchanged. In addition, the crude oils and the refining processes used to manufacture a fuel are important determinants of quality. Finally, fuel quality can either decline as a result of contamination caused by improper handling during transportation and storage or improve as a result of filtration, blending, or the injection of additives.

Fuel quality problems fall into a number of categories that reflect the factors just listed: failure to meet the fuel specification when first refined, unexpected equipment problems that occur even when the fuel specification is met, deterioration of fuel during storage, and contamination during transportation and storage.

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[1]We do not say that fuel standardization is impossible. Standardization, however, requires that all fuels meet the quality criteria of the most demanding user.

The failure of a batch of fuel to meet specification prior to purchase is a relatively easy fuel-quality problem to deal with. If the fuel is not corrected by the refiner, DoD can reject it without cost or accept it for limited use depending on the nature of the failure. Such a failure would be far more serious, however, if it was found on an industrywide or regional basis because DoD would have to either accept a lower-quality fuel or limit fuel availability.

A fuel can meet its specification completely and still cause engine problems. The Navy's JP-5 fuel specification, for example, limits aromatics (a basic family of hydrocarbon compounds) to a maximum of 25 percent because experience has shown that they leave carbon deposits inside jet engines. The Navy, however, has recently experienced problems with shrinking elastomer seals when using jet fuels that have an aromatic content around 6 percent. Since the Navy had not commonly experienced such low levels of aromatic content previously, it had not anticipated the need for a possible minimum limit for aromatics.

Fuel quality problems can also arise when fuels depart from specifications because of chemical changes that occur after purchase. Fuel stability — the ability of a fuel to resist such changes — can be divided into two categories: storage stability, which is the ability of a fuel to resist deterioration over time, and thermal stability, which is the ability of a fuel to withstand high temperatures prior to ignition without deteriorating. Storage stability problems usually result in sediment formation, which reduces fuel cleanliness. Dirty fuel can form deposits in fuel tanks and lines and can plug filters. Thermal stability problems commonly result in gum formation, which reduces engine efficiency by clogging fuel-injector nozzles and leaving deposits on engine surfaces. Storage stability and thermal stability are related because high temperatures tend to accelerate storage instability.[2] It is generally accepted that storage at 110°F for 13 weeks is equivalent to storage for 1 year at ambient temperatures (65° to 75°F).[3] However, differences exist in that some high-temperature reactions are unique and do not occur at ambient temperatures.

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[2]Some fuels researchers feel that storage and thermal stability are strongly interrelated, while others classify the two categories as distinct and separate.

[3]This correlation was first established about 30 years ago [2-1]. Additional work since that time has confirmed the relationship.

Another kind of fuel quality problem is fuel contamination during handling. Possible contaminants include other fuels, rust, dirt, and water. Fuel contaminated with water, for example, if allowed to enter a vehicle fuel tank, can cause fuel-line freezing in winter, corrosion of fuel tanks and other equipment, and filter plugging from the growth of microbiological organisms. Water is a very common fuel contaminant and normally will not cause problems if the fuel is pumped through a filter-separator, which removes both water and solid contaminants. Improper fuel handling and equipment maintenance may also exacerbate innate fuel instability. For example, failure to replace filters at the proper intervals can result in poor performance, which may be traceable to both unstable fuel and improper maintenance.

CRUDE OILS AND REFINING

Fuel quality is initially determined by the source crude oils and the refinery processes used to manufacture the fuel. (Improper handling or inadequate filtration after purchase can also affect quality by introducing contaminants or not making sure they are removed.) In theory, therefore, it should be possible to develop specifications that will prevent all fuel-quality problems except those from contamination. However, the complexity of the fuels themselves and of the mechanisms that lead to quality problems makes it virtually impossible to guarantee fuel quality through specifications alone. Specifications must be accompanied by a quality-control program throughout the fuels logistics system.

Crude oils, the raw material from which fuels are manufactured, consist of almost infinite combinations of carbon and hydrogen (in the form of hydrocarbons) plus smaller amounts of other elements such as oxygen, sulfur, nitrogen, and trace metals. The mixtures are so complex that relatively few of the hydrocarbons making up crude oils can be individually isolated. Further adding to the complexity, the content and characteristics of crude oils from different sources vary widely. That complexity is only slightly reduced when finished products are manufactured in a refinery; in fact, some refining processes actually increase the chemical complexity of the resulting products.

Refining is the manufacturing process that produces useful products (fuels, lubricants, and petrochemicals) from crude oils. All refineries first distill crude oil into various "straight-run" products or "fractions," i.e., mixtures of compounds with

similar boiling ranges. (A distinction is normally made between fractions that require further processing and products that are ready for sale.) Distillation yields in a refinery can be adjusted by drawing off products with different boiling point ranges. JP-4 jet fuel, for example, is a mixture of hydrocarbons whose boiling points are between roughly 200°F and 500°F (more precisely, the specification requires that at least 20 percent of the hydrocarbons must boil below 290°F and no more than 10 percent can boil above 470°F). JP-5 jet fuel is a different mixture consisting of higher boiling point hydrocarbons; that is, heavier compounds (at least 10 percent below 400°F and nothing above 550°F).

Distillation is a physical process that produces no chemical changes in the raw material. Although fractions from different crude oils may have similar physical properties as measured by boiling point, they may have widely differing chemical properties. Additional processing may be required to adjust chemical properties, such as aromatic content, to meet specification.

To understand the limits of distillation processes, consider what they can produce from each of two major internationally traded crude oils; Murban from Abu Dhabi and Maya from Mexico. Murban is considered a light crude because about 30 percent by volume can be distilled into gasoline and other light products boiling below 200°F. Maya, on the other hand, is a relatively heavy crude that produces only 7 percent of such products. As the two crudes are heated to higher temperatures in a refinery distillation unit, the Murban will produce more jet and diesel fuel and less of the heavy fractions (high boiling point mixtures) than Maya. Finally, since Murban has a lower sulfur content than Maya, the products derived from Murban will also tend to have a lower sulfur content.

In order for a refiner to produce the same percentage of light fuels such as gasoline, jet fuel, and diesel fuel from Maya as from Murban, the heavy fractions from the Maya crude must be sent through a conversion process. Refinery conversion processes include several different kinds of technologies to "crack" the large molecules of the heavy fractions to produce lighter, more valuable products.

Three basic conversion processes exist: catalytic cracking, thermal cracking, and hydrocracking. Catalytic cracking "cracks" intermediate weight fractions using heat and pressure in the presence of catalysts. Thermal cracking processes use heat without catalysts and are generally used to crack the heaviest fractions (the "bottom

of the barrel"). One major thermal process is coking, a controlled thermal cracking process that produces a marketable by-product, coke. Hydrocracking is essentially catalytic cracking in the presence of hydrogen; it is an extremely flexible process that can convert a variety of heavy to medium weight hydrocarbon fractions into lighter fractions.

Unfortunately, refinery conversion processes can reduce product quality. Catalytic and thermal cracking processes, in particular, can decrease both storage and thermal stability by increasing the concentration of relatively reactive compounds in the fuels they produce [2-2]. Table 2-1 shows a number of these compounds that have been linked to distillate instability and their relative concentrations in fuel produced by distillation, catalytic cracking, and thermal conversion. The concentration of most of the compounds shown increases following conversion, with the exception of acids and mercaptans (after catalytic cracking). Light products produced by a conversion refinery will be blends of straight-run and cracked material; as the degree of conversion increases, the percentage of cracked material in the final products also increases; thus, the percentage of reactive compounds also tends to increase.

TABLE 2-1

RELATIONSHIP BETWEEN FUEL INSTABILITY AND REFINERY CONVERSION PROCESSES

Fuel compounds linked to instability	Concentration after refining via:		
	Distillation	Conversion	
		Catalytic cracking	Thermal cracking
Olefins, %	0.5 - 5.0	3 - 13	8 - 30
Phenols, ppm	1 - 50	10 - 1,000	10 - 5,000
Thiophenols, ppm	1 - 10	10 - 500	10 - 500
Acid No., mg KOH/g	0.0 - 1 3	0.0 - 0 1	0 0 - 0 2
Pyrrole N, ppm	0 - 10	0 - 200	0 - 100
Mercaptans, ppm	0 - 200	0 - 100	0 - 400

Source: M W Schrepfer et al [2-2]

Olefins, for example, are an important class of hydrocarbon compounds produced by catalytic and thermal cracking processes. Olefins are chemical compounds that are relatively reactive or unstable. Specifically, olefins contain unsaturated (double) bonds between carbon atoms that are more reactive and thus less stable than the single carbon bonds and ring structures found in crude oils. Jet fuel specifications limit olefin content to a maximum of 5 percent, and for that reason, very little cracked stock (the output from cracking processes) is blended into jet fuels. Cracked stock is, therefore, available mainly for gasoline, diesel fuel, and home heating oil.

Catalytic cracking can also reduce the ignition quality of diesel fuels (measured as cetane number). Catalytically cracked fractions may have significantly lower cetane numbers than straight-run fractions from the same crude oil [2-3].

Hydrocracking is the third major conversion process. Unlike the other two processes, hydrocracking splits up heavy molecules in the presence of hydrogen. As the heavy hydrocarbon molecules split apart, hydrogen combines with the new, smaller molecules at the locations at which the breaks have taken place. This tends to result in more stable products with far fewer olefins, for example, than the products of other conversion processes. Hydrocracking, however, tends to increase the peroxide concentration of a fuel, which can lead to decreased stability by accelerating fuel oxidation. Peroxides can also attack elastomer seals, leading to leaks in the fuel system.

Not all refinery processes reduce product quality. In addition to distillation and the conversion processes, other refinery processes (generally known as finishing processes) increase product quality by modifying certain fuel properties. The two main classes of finishing processes are desulfurization, which improves quality by removing sulfur, and the numerous processes that increase gasoline ignition quality (octane).

FUEL SPECIFICATIONS

Fuel specifications are essential in order to acquire and monitor fuels. Both the buyer and the seller need specifications to determine what constitutes appropriate fuel for a given purpose. A fuel specification consists of a list of required laboratory procedures (tests) to measure certain fuel properties together with the maximum or

minimum allowable limits on the results of those tests. In addition to purchase specifications, DoD has also established guidelines, consisting of subsets of the full battery of specification tests, to monitor fuel quality during transportation and storage.

The links between fuel specifications and engine performance are approximate but generally satisfactory as a means for monitoring fuel quality. Petroleum fuels are mixtures of many complex compounds. The exact nature of these product mixtures varies with the crude oil types from which they are made as well as with the refinery processes used to produce them. While specifications may not define a fuel exactly, they place limits around its most important characteristics. As a result, two fuels that meet the same specification will not necessarily be chemically identical and may not behave in precisely the same way.

A specification is established through the following five steps: (1) setting engine performance requirements, (2) translating those requirements into fuel requirements, (3) determining the properties of a fuel that affect the various performance requirements, (4) developing laboratory tests that will measure these fuel properties, and (5) placing acceptable limits on the laboratory test results to ensure satisfactory equipment performance. A fuel specification consists of a list of important properties, the test procedures that must be used to measure those properties, and the maximum or minimum acceptable results of those tests. Table 2-2 illustrates the links between engine performance requirements, fuel requirements, fuel properties, and acceptable test results for Naval Marine Distillate (F-76) and a commercial diesel fuel (2-D). For simplicity, Step 4, the required test procedures, has been omitted. The differences between the two distillate specifications shown in Table 2-2 arise from different engine performance requirements.

The first two steps in the specification-setting process outlined above (and illustrated in Table 2-2) relate engine requirements to fuel requirements. For example, its fuel should permit a diesel engine to start readily and to produce maximum power. To meet those engine requirements, a diesel fuel must meet a number of performance requirements: it must vaporize sufficiently to mix with air and burn cleanly and at the right instant (i.e., ignite readily) without leaving residues.

TABLE 2-2

RELATIONSHIP BETWEEN ENGINE PERFORMANCE REQUIREMENTS AND DIESEL FUELS SPECIFICATIONS

Engine performance requirement	Fuel requirement	Fuel property	Acceptable test results	
			F-76 (MIL-F-16884H)	ASTM D 975 (2-D)
Starts readily; produces maximum power	Readily ignitable; clean burning	Cetane no., min	45	40
		Distillation (volatility)		
		50% point, °F	record	--
		90% point, °F, min/max	675/-	540/640
		End point, °F, max	725	--
		Residue and loss, %, max	3.0	--
		Sulfur,%(weight),max	1 00	0 5
		Carbon residue (10% bottoms),%,max	0 20	0.35
Operates consistently and smoothly	Pumpable at low temperatures (fluidity); readily atomized	Viscosity, cSt at 100°F	1 7 - 4 3	1 9 - 4.1
		Pour point, °F, max	20	--
		Cloud point, °F, max	30	--
Is efficient	Maximum heat content (consistent with ignition requirements)	Gravity, deg API	record	--
		Gravity, specific	record	--
Refuels safely	Safe to handle	Flash point, °F, min	140	125
Requires low maintenance; avoids filter-clogging	Water-shedding ability;[a]	Demulsification time, max	10	--
	Reliable after prolonged storage (stable); noncorrosive	Color, max	3	--
		Appearance	clear/bright	--
		Water-and-sediment, %(volume), max	0 01	0 05
		Total acid number, mg KOH/g, max	0 30	--
		Neutrality	neutral	--
		Copper strip at 212°F, max	No 1	No 3
		Sulfur,%(weight), max	1 00	0 5
		Accelerated stability, mg/100 ml, max	1 5	--

Note: Dashes indicate property need not be measured. "Record" indicates that property must be measured, but no limit is placed on the test result. For simplicity, the required test procedures have been omitted.

[a] ML-F-16884H limits the number of acceptable additives because of their tendency to stabilize emulsions.

The third step in the specification-setting process relates fuel requirements to fuel properties. Experience has shown that the primary diesel properties linked to ignition and vaporization are cetane number and volatility (or boiling range). Cetane number refers to the ability of a diesel fuel to ignite in the engine cylinder; the higher the cetane number the better the ignition quality of the fuel.[4] Diesel fuel

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[4]Diesel fuel is not ignited by a spark plug but rather by the heat produced by the compression of gas inside a cylinder. Cetane number is determined by comparing a fuel against a varying mixture of two reference fuels, cetane and alpha-methyl-naphthalene. For example, a fuel with cetane number 45 matches the self-igniting quality of a mixture of 45 percent cetane and 55 percent alpha-methyl-naphthalene in a test engine.

volatility is important because the fuel must vaporize before it can ignite. Volatility is measured by a distillation test that determines the temperatures at which specific percentages of the fuel have boiled off. For example, the higher the temperature at which 90 percent of the fuel has boiled off (and also the higher the final boiling point), the more difficult it is for the fuel to vaporize completely in the engine cylinder.

As illustrated in Table 2-2, the F-76 specification requires a cetane number of at least 45, which is more demanding than the minimum commercial specification of 40. Table 2-2 also shows the various maximum and minimum distillation temperatures.

CHAPTER 3

FUEL QUALITY TRENDS

Observers within DoD's fuels community differ in their assessments of the severity and extent of the fuel quality problems that DoD has encountered. Available evidence on fuel quality trends, however, does not show DoD fuel quality problems to be relatively numerous.

In our assessment, we measured fuel quality trends in two ways: first, by tracking changes in aggregate fuel properties over time; and second, by estimating the frequency of actual fuel-related problems during fuel delivery, storage, and use. We concentrated on the major DoD mobility fuels – jet and diesel fuel – that power aircraft, ships, and ground vehicles. Jet fuel accounted for 76 percent of the petroleum mobility fuels transferred from DLA to the Military Departments in FY 1986, while diesel fuel accounted for 21 percent [3-1].

FUEL PROPERTY CHANGES

Analysis of annual changes in fuel properties shows that relatively few jet fuel properties deteriorated during the late 1970s and early 1980s; the majority of properties measured either improved or stayed the same. Diesel fuel properties, by contrast, exhibited more deterioration than jet fuel properties. This section outlines these findings; Appendix A provides a more detailed discussion of our methodology and findings.

Several sets of data exist that measure fuel property changes over time.[1] The Air Force has published data on the properties of jet fuel (JP-4), while the Navy monitors both jet fuel (JP-5) and Naval Marine Distillate (F-76), a diesel fuel. The Army's General Materiel and Petroleum Activity, New Cumberland, Pa., maintains records of specification test results on Army diesel fuels (DF-A, DF-1, and DF-2). In addition, the National Institute for Petroleum and Energy Research (NIPER)

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[1]References to these data sources are presented in Appendix A.

publishes summaries of its annual surveys of various petroleum products, including military jet fuels and commercial diesel fuels.

The data from all of these sources measure selected fuel properties by averaging the results of specification tests conducted at the time the fuel was refined. These annual averages reveal changes in fuel properties over time, and, thus, whether fuel quality has deteriorated or improved during the period of time covered by the data. Fuels that do not meet specification are not included in the data unless a waiver has been granted since a fuel is not normally purchased if it fails the specification.[2] In addition, the data do not measure post-purchase changes in fuel properties caused by fuel instability.

The survey results for military fuels are summarized in Table 3-1. Of the 19 JP-4 properties measured in the Air Force survey, 11 properties did not show statistically significant changes between 1960 and 1981, 7 properties improved, and 1 property worsened. The NIPER JP-4 survey measured 18 different jet fuel properties between 1974 and 1984; again, more than half showed no statistically significant change, 3 properties improved, and 4 properties got worse. The differences between the Air Force and NIPER results are due in part to the different time periods covered and the different properties measured and in part to the different sampling techniques. (The methods used to evaluate the data are detailed in Appendix A.)

According to both JP-4 surveys, the smoke point worsened over the period measured while total sulfur content showed an improvement. Moreover, the results of both surveys are consistent in the sense that no properties simultaneously improved according to one survey and worsened according to the other.

The Navy's survey of JP-5 properties tracked 33 jet fuel properties in the period 1977 through 1983. As shown in Table 3-1, 25 properties showed no significant change, 4 improved, and 4 worsened. The JP-5 data are consistent with the JP-4 results; in other words, no properties simultaneously improved in one and worsened in the other. We have not included the results of the NIPER JP-5 survey in Table 3-1 since the sample was too small.

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[2] Army diesel fuel is an exception, which we discuss in more detail later in this chapter.

TABLE 3-1

CHANGES IN MILITARY FUEL PROPERTIES OVER TIME

The number of measured fuel properties that . . .	Military jet fuels			Military diesel fuel
	JP-4	JP-4	JP-5	F-76
Got worse	1	4	4	8
Improved	7	3	4	2
Stayed the same	11	11	25	8
Period measured	1960/70 – 81	1974 – 84	1977 – 83	1979 – 84
Data source	Air Force	NIPER	Navy	Navy

Table 3-2 indicates the severity of the changes in those properties that worsened. Using statistical methods, we developed trend lines to measure changes over the periods covered by the data; the table indicates how many years (from 1987) it would take to exceed the current specification if those past trends continued *into* the future. (The numbers in the table are not forecasts; they merely indicate the degree of change.) Figure 3-1 shows how the table works, using the freeze point of JP-4 as an example; the figure displays the actual average values for JP-4 between 1974 and 1984, the trend line, and the specification limit. The trend line crosses the limit in 1991, four years after 1987. As Table 3-2 shows, only two jet fuel properties deteriorated sharply, the JP-4 freeze point and the peroxide level of JP-5. The increase in peroxide content prompted the Navy to add a peroxide limit to the JP-5 specification where none had existed previously. In addition, the JP-5 water separation index (WSIM), which measures a fuel's ability to separate from water, declined. However, that decline is somewhat misleading. The specification differs depending upon the presence or absence of an additive that affects the fuel's ability to separate from water. The yearly averages, therefore, consist of an unknown mix of fuels with and without additives, and we found difficulty in drawing any conclusions from these statistics. The remaining properties remained well within the specification limits.

TABLE 3-2

FUEL PROPERTIES THAT WORSENED

Fuel properties	Number of years from 1987 until specification exceeded (if past trends continue)
JP-4 (Air Force data):	
Smoke point	85
JP-4 (NIPER data):	
Freeze point	4
Smoke point	17
Aromatics	67
Water tolerance	No limit[a]
JP-5 (Navy data):	
Peroxide	8
Distillation loss	35
Aromatics	36
WSIM	NA[b]
F-76 (Navy data):	
Cetane number	1
Viscosity	17
Cloud point	18
Pour point	19
Distillation 90%	26
Distillation 50%	No limit
API gravity	No limit
Aniline point	No limit
1-D (NIPER data):[c]	
Flash point	32
Sulfur content	94
Aniline point	No limit
2-D (NIPER data)	
No properties got worse	

Note: These numbers do not constitute forecasts; they only indicate the extent to which properties deteriorated during the period measured

[a] Indicates that fuel specification includes no limit for that property

[b] Data consist of fuel with/without additives

[c] Compared to Grade DF-1 military specification

3-4
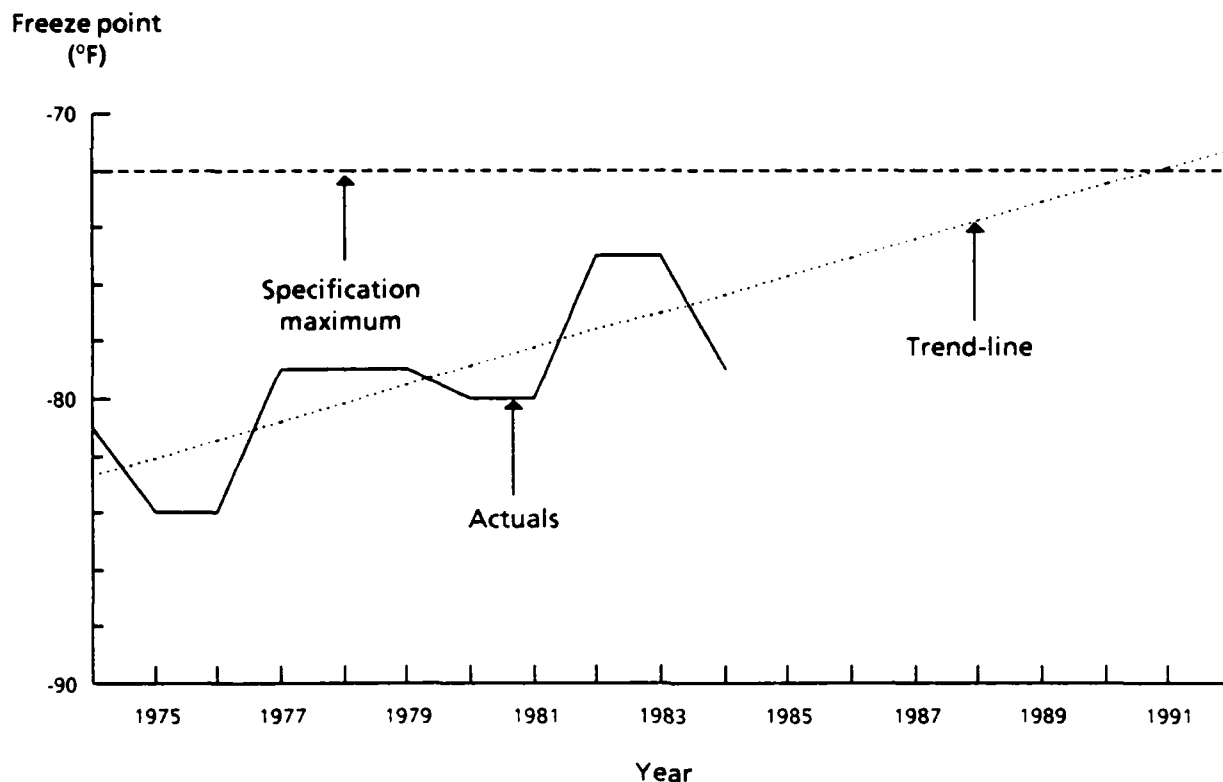
FIG. 3-1. JP-4 FREEZE POINT TRENDS

Our analysis of the Navy's time-series data on Naval Distillate Fuel (F-76) shows that eight properties worsened, only two improved, and eight remained unchanged over the period 1979 through 1984. Again, Table 3-2 indicates the severity of the change experienced by the eight F-76 properties that worsened. The cetane number fell sharply between 1979 and 1984 (shown subsequently in Figure 4-2), but the other properties limited by the F-76 specification deteriorated only slightly. The Navy does not specify a limit for three of the eight properties that worsened.

Because data covering a sufficient length of time are not available for Army diesel fuels, we examined the property trends of commercial diesel fuels for the United States as a whole. Army fuel specialists hold differing opinions regarding the similarities between Army diesel fuels and commercial diesel fuels. One view is that " ... the VV-F-800 [Federal specification diesel fuel] procured in CONUS represents essentially commercial ASTM D975 product, . . . " [3-2] (ASTM D975 is the specification for 2-D diesel fuel). Another view is that most of the diesel fuel used by

the Army is a distinct military product. These two views are not as far apart as they appear, however, because VV-F-800 is a distinct military fuel but its differences from commercial diesel fuel specifications are minor. Army diesel fuels basically carry two extra quality requirements: a requirement that the fuel be "clear and bright" and that it pass a storage stability test.

Because the military and commercial specifications are so similar, we felt that NIPER data on commercial U.S. diesel fuels could serve to approximate Army diesel fuel quality trends. We used NIPER data to track the properties of commercial diesel fuels — "Type City Bus" diesel fuel, a relatively high quality fuel, and "Type Truck-Tractor" diesel fuel — from 1970 through 1982, and two closely related commercial diesel fuels, 1-D and 2-D, a data-series starting in 1979.[3] As shown in Table 3-3, most of the City Bus diesel fuel properties remained unchanged, while four properties worsened and none improved. The Truck-Tractor diesel fuel did not fare as well; only five properties remained unchanged, seven properties worsened, and none improved. In particular, the cetane number of both fuels declined fairly steeply during the period covered, and by 1980, the cetane number of both commercial fuels had approached the Army's minimum specification limit. This trend prompted the Army to lower the minimum acceptable cetane number from 45 to 40 (the commercial minimum).

According to NIPER's more recent data, however, commercial diesel fuel cetane numbers did not continue to decline and, in fact, showed no consistent trend either up or down between 1979 and 1985. Figure 3-2 illustrates the changes in cetane number for all four diesel fuels tracked by NIPER. More generally, commercial diesel fuel properties exhibited fewer declines in the more recent period. In all, only three properties of 1-D diesel fuel worsened, while 11 remained unchanged; none of the properties of 2-D fuel exhibited a significant change for either better or worse in this decade. Moreover, as shown in Table 3-2, two of the 1-D properties that worsened remained well within the specification limits and the other is not considered important enough to be included in the specification.

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[3]Since we are interested in examining the most current fuel quality trends (with an eye to the future), the NIPER data on City Bus and Truck-Tractor fuels are no longer of great interest. Nevertheless, we have discussed those older trends because they have been highlighted in numerous publications on fuel quality. No one, to our knowledge, has yet discussed the implications of NIPER's more recent diesel fuel data. (NIPER itself, in a 1986 study, ignores its own more recent and more optimistic data [4-1].)

TABLE 3-3

CHANGES IN COMMERCIAL FUEL PROPERTIES OVER TIME

The number of measured fuel properties that . . .	Premium diesel fuels		Regular diesel fuels	
	City Bus type	1-D	Truck-Tractor type	2-D
Got worse	4	3	7	0
Improved	0	0	0	0
Stayed the same	8	11	5	14
Period measured	1970 – 82	1979/81 – 85	1970 – 82	1979/81 – 85
Data source	NIPER	NIPER	NIPER	NIPER

FUEL QUALITY PROBLEMS IN THE FIELD

This section describes our findings on the frequency and nature of fuel quality problems experienced in the field. Such measurement is necessary to form a complete assessment of DoD's fuel quality situation. The ultimate test of any fuel is whether it produces adequate equipment performance. The averages of specification tests captured by time-series data do not necessarily predict equipment performance.

We found little data directly relating fuel quality problems to lower engine performance. The absence of such data seems to result from two facts. First, most fuel quality problems are detected at purchase or during fuel transportation and storage and can be corrected before they affect engine performance. Second, DoD does not maintain systematic records of fuel quality problems found either in the logistics system or by equipment operators.

To estimate the scale of problems in the field, we interviewed personnel at DFSC and the Military Departments. DFSC is exposed to most distribution and storage problems, while the Military Departments are exposed mainly to end-user problems. DFSC directly purchases, distributes, and stores the majority of DoD fuel, including war reserve fuels. It ultimately transfers fuels under its control to the Military Departments for end-user storage and use. The fuels that are stored and transported by DFSC are referred to as "bulk" fuels.
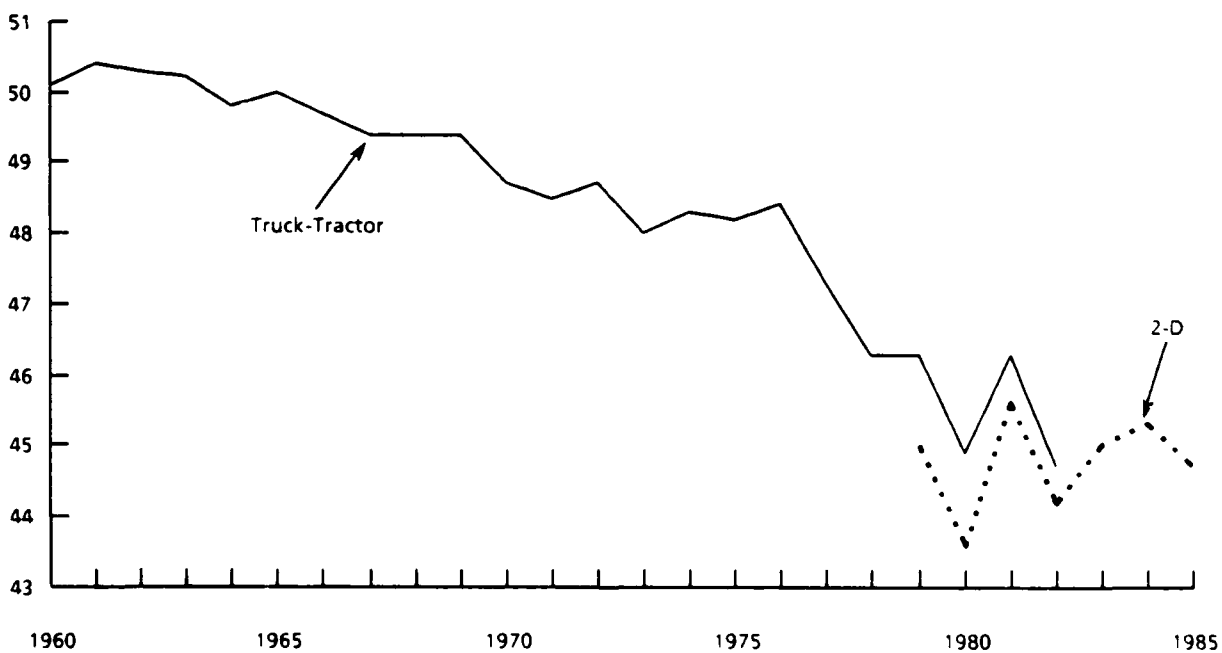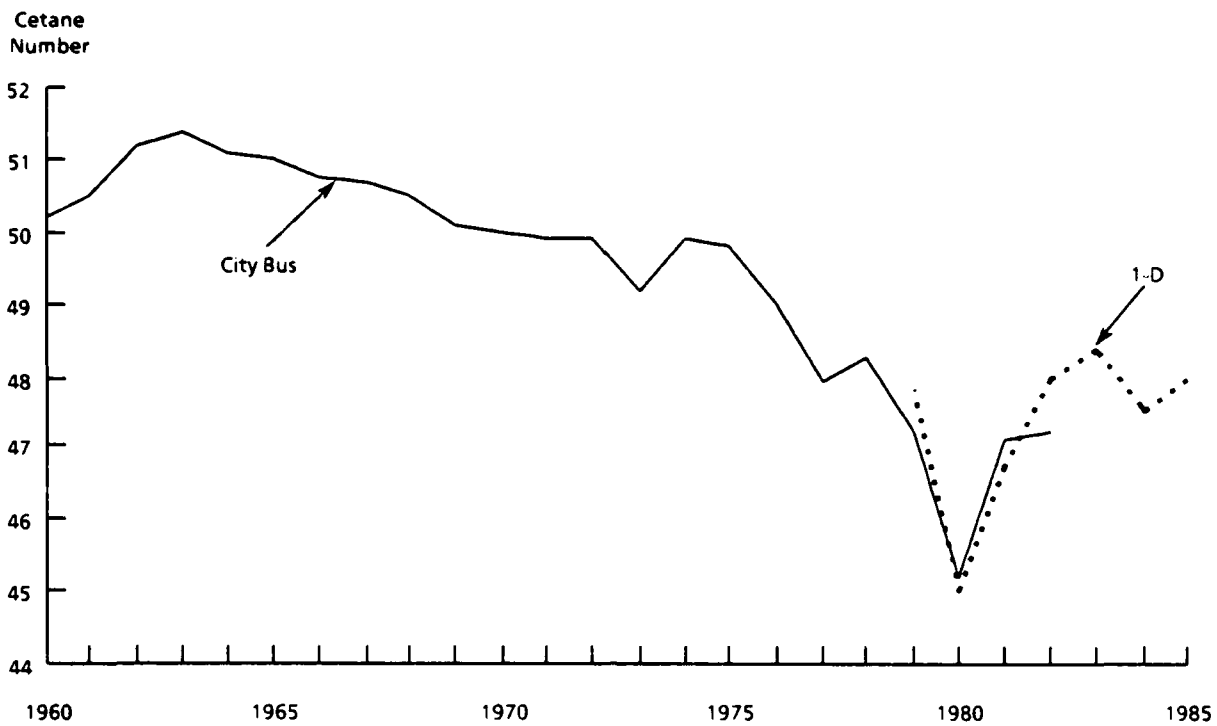
FIG. 3-2. COMMERCIAL DIESEL FUEL IGNITION QUALITY TRENDS

Source: NIPER

3-8

Defense Fuel Supply Center

Bulk fuels handled by DFSC are mainly jet fuels and naval distillate fuel. They make up the largest volume of DoD fuels. Recent DFSC problems with bulk fuels are listed in Table 3-4. The most frequent problems involved fuel storage instability, that is, fuel departing from specification after purchase. The table does not include all problems experienced with DFSC bulk fuels since less-severe quality problems are routinely handled by DoD fuel terminals without being brought to the attention of headquarters. All of the problems experienced by DFSC were detected by testing the fuel before it was used. Moreover, the magnitude of those problems is not large; the volumes shown in the third column of Table 3-4 should be compared to DFSC's total worldwide inventories, which range from 87 million barrels in FY 1984 to 90 million barrels in FY 1986 (excluding stocks in transit) [3-1].

TABLE 3-4

RECENT FUEL QUALITY PROBLEMS ENCOUNTERED BY DFSC

Year	Product	Volume (000s of barrels)	Location	Problem
1984	F-76	500	San Pedro, Calif.	Changed color; also, particulate buildup
1984	F-76	100	Oman	Turned dark rapidly; also, particulate buildup
1984-5	JP-4	NA	Various	Unacceptably long filtration time
1984-5	JP-5	NA	West Coast	Green product; made from Alaska North Slope crude
1984-5	F-76	NA	West Coast	Stability problems with product made from Alaska North Slope crude
1985	JP-5	117	Oman	Turned dark within 2-3 months but did not go off specification
1985	JP-5	60	Mombassa	Turned dark
1985	F-76	10	Norfolk, Va	Turned dark in transit from Gulf Coast refinery
1985-6	JP-4	NA	Tulsa, Okla.	Thermal stability deteriorated

Source: Quality Assurance and Technical Information Branch, DFSC

Note: NA indicates data not available

Six of the nine problems presented in Table 3-4 involve a color change in the fuel. Although color change, or darkening of the fuel, is an indication of chemical changes in the fuel, it does not invariably indicate sediment formation and therefore is not a foolproof indication that the fuel will no longer perform well. Performance

degradation depends on the type of change taking place; the mechanisms that cause a fuel to change color may be different from those that produce filter-clogging sediment. Nevertheless, color change is important because it is a very easy test to make and a batch of fuel will usually be rejected by end-users if it has turned dark, even if the fuel is otherwise of acceptable quality.

DFSC has recently experienced a number of unacceptable results on the filtration test for JP-4 fuel. The filtration test is included in military jet fuel specifications to indicate potential operational problems in fuel delivery systems since jet fuels are filtered a number of times prior to final delivery into aircraft. The problem, once detected, can often be cured by letting the fuel sit undisturbed for several days; otherwise the jet fuel is restored by filtering through a clay medium.[4] The causes of poor filtration are not well understood. The phenomenon appears to have various causes, of which the most common is probably the presence of various sediments and gums [3-3]. Excess concentrations of certain additives, such as jet fuel de-icer, and interaction among additives can also lead to poor results on the filtration test.

Three of DFSC's nine reported problems involved fuel in long-term storage in the Middle East. Fuels stored over a long period are generally more vulnerable to deterioration for several reasons. First, sediment-forming reactions are given a longer time in which to work and a larger amount of sediment can collect. Second, fuel that remains isolated in long-term storage does not have the opportunity to commingle with a variety of other batches of fuel of different ages and different characteristics. Commingling of fuels tends to eliminate many potential quality problems since the majority of fuels are within specification limits sufficiently to dilute effectively any fuel that is slightly off specification.

Fuel stored in above-ground tanks in the Middle East is subject to relatively high ambient temperatures, and high temperatures accelerate sediment-forming reactions and thus decrease fuel stability. Below-ground tanks are more effective in extending fuel storage stability than above-ground tanks because they keep fuels

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[4]NIPER researchers were unable to reproduce excess filtration times for three of five fuels recently submitted to them as "problem fuels"[3-3]. Filtration test results on the same batch of fuel can vary widely over time and tend to be higher just after the fuel has been moved.

relatively cool and reduce temperature fluctuations, but they are not always available. DoD uses underground storage at many domestic and European locations.

Army

Army data on fuel quality problems in the field are the most systematic of those assembled by the Military Departments. Data assembled by fuel experts at the Army Belvoir Research, Development and Engineering Center show that the reported number of diesel fuel problems is quite small despite the fact that diesel fuels delivered to the Army frequently fail to meet specification.

The Belvoir Center and the General Materiel and Petroleum Activity (GMPA) both serve as points-of-contact for fuel problems within the Army. In addition, GMPA employs a staff of six or seven fuels technicians who travel to Army facilities in the U.S. and abroad, advising on fuel problems and other fuel-related issues.

Belvoir Center data show that an average of only five diesel fuel quality problems a year have been reported since 1980 [3-4][5]. That number is relatively small when compared with about 16,800 diesel fuel deliveries in a single year.[6] The number is also small compared with the number of Army diesel engines (which includes both portable field generators and vehicle engines). Reported problems remain infrequent despite the fact that the Belvoir Center recently instituted a hot line to tap more directly into Army fuel quality problems in the field. The Belvoir Center recently issued a fuel quality questionnaire to the field (March 1987); the results are not yet available.

The contributing factors behind the diesel fuel quality problems reported to the Belvoir Center are varied; they are summarized in Table 3-5 [3-4]. Unstable fuel, the most common factor, was involved in almost two-thirds of the occurrences. In most cases, however, instability was only one of the contributing factors. Additional factors included water in the fuel and improper maintenance. The most common manifestation of problem fuel was filter plugging, which occurred in about

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[5]M.E. LePera of the Belvoir Center supplied additional data to those contained in Reference [3-4]. The resulting list of 55 problems experienced between 1965 and 1985 excludes three instances in which Fort Belvoir was asked for technical advice when fuel was to be stored aboard vehicles for an extended period. The Belvoir Center's advice was intended to avoid potential problems.

[6]Estimate of CY 1986 diesel fuel receipts made by Don Foster of GMPA. The estimate was reached by dividing 84 million gallons, the approximate volume of diesel fuel received (within the continental U.S., CONUS), by 5,000 gallons, the average commercial delivery.

60 percent of the cases. Filter plugging is a result of dirty fuel and is produced not only by unstable fuel but also by microbiological debris resulting from water in the fuel system.

TABLE 3-5

U.S. ARMY DIESEL FUEL FIELD PROBLEMS

(1965 – 1985)

Contributing factors identified	Number of occurrences	Percent of total
Unstable fuel only	10	18
Unstable fuel plus other factors	22	40
Other factors only	21	38
Not determined	2	4
Total	55	100

Source: U.S. Army Belvoir Research, Development and Engineering Center

Published Army data document relatively few serious diesel fuel problems despite the fact that Army diesel fuel is probably the most susceptible of all DoD distillate fuels to stability and handling problems. Most Army ground fuel is obtained through DFSC's Posts, Camps, and Stations (PCS) acquisition program rather than through bulk deliveries to DFSC terminals. The frequency and small size of the average PCS delivery mean that the Army does not find it practical to test every delivery of PCS fuel. Also, relatively little Army diesel fuel is filtered before use to remove possible contaminants. Army diesel fuel, unlike jet fuel or naval diesel fuel, must sometimes be stored in vehicle tanks and in portable generators for prolonged periods. As Army fuel researchers have stated, in-vehicle storage is the least desirable means of storing petroleum fuel; storage in bulk fuel tanks is preferable.[7]

GMPA, whose laboratories are used to test Army diesel fuel, found that 15 percent of all the Army diesel fuel samples tested in 1986 failed to meet one or more of the Army's diesel fuel specifications; it tested about 8 percent of all Army diesel fuel deliveries after acceptance. Table 3-6 summarizes the specification

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[7]"The amount of fuel left in the stored vehicles is usually small compared with the fuel tank size and results in maximum environmental effects on the remaining fuel. . . ." [3-5]

failures documented by GMPA. Forty percent of the failed fuels exceeded the maximum distillation limits; that is, the fuel was too heavy and possibly could cause ignition problems such as poor starting or loss of power. Failure to meet cloud-point and flash-point limits were the next two most common failures. Cloud-point failures have resulted in cold-weather waxing problems within the Army and those problems are not included in the Belvoir Center's data. Diesel fuel with a high cloud-point (the temperature at which wax crystals form) can plug engine filters during the winter.

TABLE 3-6

1986 ARMY DIESEL FUEL SPECIFICATION FAILURES

Failed specification	Percent of failures
Distillation	40
Flash point	18
Cloud point	11
Viscosity	10
Cetane number	9
Sulfur	7
Appearance	3
Particulates	2
Total	100

Source: U.S. Army General Materiel and Petroleum Activity

Waxing problems, however, do not always indicate poor quality fuel. Fuel with above-specification cloud-point is not the only cause of cold-weather waxing. It can be produced by unexpectedly cold weather or movement of vehicles from a warm climate to a cold one (the cloud-point limit varies with geographic area). Another possible cause of waxing problems is changing engine design. Engines whose fuel lines run close to the engine block are less prone to wax formation than engines whose fuel lines are located in cooler areas.

With the exception of cold-weather waxing problems, the Army does not have data that link these specification failures directly to engine or other fuel problems. Many such problems, including poor starting, loss of power, or reduced fuel efficiency, may have been compensated for, unnoticed, or otherwise ignored.

Navy and Air Force

In 1981, the Navy experienced two severe shipboard fuel quality problems. The mission of the *USS Deyo* (DD 989) was aborted because of excessive engine injector nozzle deposits attributable to fuel thermal instability. In the same year, the *USS Samuel Eliot Morison* (FFG 13) was forced to return to port when the fuel became so dirty that filters were being replaced almost constantly. These experiences led to Navy fears that fuel quality had passed a critical threshold. These two problems, however, have thus far remained isolated. (The fuel being burned aboard both vessels reportedly came from a single Louisiana refinery that has since shut down.)

In addition to the jet fuel filtration problems that were reported by DFSC (and shown in Table 3-2), the Air Force has reported recent problems with low jet fuel "lubricity" resulting primarily in shorter fuel pump life. Lubricity, which refers to the natural lubricating properties of petroleum fuels, is a difficult property to define precisely. Nevertheless, certain fuel pumps and other fuel system components have been designed to rely on that natural lubricating property. Air Force fuels researchers who are currently working to define a specification test for lubricity believe that reduced lubricity is related to refinery hydrotreating and hydrocracking processes.

SUMMARY

Most jet fuel properties have remained relatively unchanged over time, while a larger number of diesel fuel properties have deteriorated. Nevertheless, most fuel properties (including commercial diesel fuel properties) remain well within the limits set by the military specifications.

Similarly, the evidence on field problems appears to indicate that DoD has experienced relatively few fuel quality problems during fuel storage and use. DFSC has seen few recent fuel quality problems despite the fact that it maintains DoD's largest fuel inventory. The Army, with the most systematic data of all the Services, has also documented relatively few serious problems.

CHAPTER 4

FUEL QUALITY ISSUES

Some DoD fuel personnel are concerned that fuel quality may be declining beyond the ability of existing quality control procedures to maintain it. They have expressed concern that changes in the oil industry have led to the use of lower-quality crude oils and more intensive manufacturing processes, resulting in lower-quality products. By contrast, other fuel quality personnel feel that in recent years, if fuel quality has changed at all, it has not changed substantially. The evidence on fuel quality trends presented in the previous chapter needs to be examined in the light of these different perspectives.

ARE FUEL PROBLEMS UNDERREPORTED?

The fact that in DoD only the Army maintains systematic data on fuel-related problems in the field raises the possibility that serious fuel problems are occurring more often than the available evidence indicates; that is, fuel problems might not be reported to higher levels. If true, the evidence presented in Chapter 3 understates the true number of fuel quality problems experienced by DoD. The idea that some fuel quality problems go undetected or unreported is reasonable. Nevertheless, for the reasons detailed below, we believe that the evidence in Chapter 3 correctly reflects the magnitude of DoD's fuel quality situation. The number of bulk fuel problems is relatively small. The number of documented problems resulting from Army ground fuels in the PCS program is also relatively small but the implications for underreporting are not clear cut. Nevertheless, the PCS program accounts for far fewer fuels than DLA's bulk fuels.

Engine performance problems resulting from poor-quality fuel may appear as mechanical problems rather than as fuel problems. While such appearance can delay recognition of fuel quality problems, it is unlikely to hide serious problems indefinitely. For example, fuel problems may manifest themselves as a need for more-frequent engine overhauls or or a higher rate of filter replacement. When fuel gets so dirty that the rate of replacing fuel-pumping equipment filters becomes burdensome, some equipment operators have been known to keep operating without

filters. Although that practice provides a temporary solution, it eventually leads to clogging of engine-mounted vehicle filters. Thus, it can only delay eventual recognition of a fuel quality problem.

Field Practices

The fact that all fuel quality problems are not brought to the attention of higher-level officers may sometimes reflect good management. Some field solutions can be cost-effective. For example, the Army has experienced a number of cold-weather waxing problems with diesel fuel. It is possible that not all such problems have been reported to the Belvoir Center or GMPA; some Army installations may be eliminating filter plugging by blending the problem fuel with kerosene (which lowers the cloud point). This field solution is usually the recommended short-term procedure. (In Europe the Army has reached a long-term solution to waxing problems in the M-1 tank by using JP-8 fuel, which has a cloud point significantly lower than conventional diesel fuel.)

Fuel contamination after purchase does not necessarily indicate that field personnel are not reporting fuel quality problems. It is generally not efficient practice to maintain petroleum fuels in a totally uncontaminated state throughout the logistics network although it is certainly necessary that the fuel be of high quality once it enters the equipment that it is to power. Water, for instance, is a common contaminant in fuel terminals; however, a thin layer of water at the bottom of a storage tank containing jet or diesel fuel is perfectly acceptable. That water can be removed by pumping out the bottom of the tank where the water settles, by putting the fuel through a series of water-settling tanks, or by passing the fuel through a filter-separator. Blending of fuels and reinjection of additives are other common, low-cost procedures for maintaining fuel quality. Such procedures are standard practice in the oil industry.

Bulk Fuel Testing

Serious quality problems among bulk fuels are not likely to remain undetected because DoD's logistics system subjects DoD bulk fuels to frequent tests. Every batch of bulk fuel purchased by DFSC is checked at the refinery by a Quality Assurance Representative (QAR) who is a DLA employee. The QAR carries out the

full range of specification tests. If the fuel fails the specification limit for any one test, it is rejected unless a waiver is granted by the contracting officer.

At each subsequent transfer point, some specification tests (but not the full range) are carried out to monitor the batch of fuel as it passes through the distribution and storage network that comprises DoD's bulk fuel logistics system. Vessels that carry DoD fuels are inspected prior to loading, and the fuel itself is then tested at loading and discharge. If a fuel remains in dormant storage for more than 6 months, it is tested again for the range of properties subject to deterioration as a result of storage instability. If the fuel shows signs of deterioration at any point, it is blended with other batches to correct the problem and used immediately to prevent further deterioration. Other problems may require reinjection of additives or filtration to remove sediment.

In addition to testing bulk fuels frequently, DFSC fuel terminals follow a first-in, first-out stock rotation policy to prevent overly long storage of any one batch. The normally high inventory turnover at CONUS bulk fuel terminals, together with the normal mixing of different batches of fuel, effectively prevents storage instability from becoming a significant CONUS problem.

Finally, military personnel have the right to reject fuel from DFSC and will do so if the fuel appears to be below acceptable quality. The cost of correcting most problems is relatively low compared with the potential costs of using poor-quality fuel.

PCS Fuel Testing

Army ground fuels obtained through the PCS program are not subject to the same rigorous tests as DoD's bulk fuels. In addition, most Army installations do not employ fuel filters or filter separators in their fuel-handling systems. In many cases, the required capital investment would be too high since the volume of fuel handled by such installations is often very small. (Fuels destined for tactical units, however, are handled more carefully because of the higher costs of potential problems.)

The differences in handling between PCS and bulk fuels are important in light of the fact that a significant number of Army diesel fuels (about 15 percent) failed one or more specification limits in 1986. It is possible that some Army fuel problems,

such as poor starting or loss of power, are compensated for by equipment operators and are never reported.

On the other hand, evidence indicates that fuel stability problems do not occur on a large scale in the Army. The Army has recommended a diesel fuel stability additive for use when an installation is experiencing unusual problems with fuel deterioration. The additive is inexpensive (about one cent per gallon) but is not required for every batch of military diesel fuel. Turnover at PCS refueling points is normally extremely short and tends to reduce storage stability problems (other than when vehicles are stored fully-fueled).

Summary

Bulk Fuels

In summary, while it is plausible that some bulk fuel quality problems may go undetected or may be corrected with inefficient procedures, it is unlikely that more than a few such problems are able to slip past DoD's thorough bulk fuel testing procedures. Many field solutions to fuel problems are efficient and accepted industry practice. Moreover, frequent commingling and relatively rapid turnover of domestic bulk fuels helps prevent stability problems from appearing. Finally, personnel from the Military Services are unlikely to accept fuels from DFSC when they even suspect that the quality of those fuels is less than acceptable.

Several years ago the Defense Audit Service reached a similar conclusion after examining DoD's fuel storage practices to ensure that fuel was not being stored for excessive periods, was being properly monitored, and was not being unnecessarily downgraded. Its report, issued in 1981, concludes that "Long-term storage of fuel in DoD has not been a significant problem. Only minor quantities of fuel were reprocessed or disposed of because of deterioration or contamination" [4-1].

PCS Fuels

We found that Army fuels specialists hold different opinions about the state of PCS diesel fuel quality. While it is true that a high percentage of PCS diesel fuels delivered to and accepted by Army installations subsequently failed to meet the Army's diesel fuel specifications (15 percent in 1986), it is equally true that the Army has documented very few equipment problems resulting from those specification failures (5 per year between 1980 and 1985, plus an unspecified number

of waxing problems). Two hypotheses are possible. The first holds that documented problems accurately represent the magnitude of Army fuel problems and therefore, that specification failures are irrelevant. That is, Army diesel fuel is overspecified since even fuels that do not meet the specification produce acceptable performance. The second hypothesis holds that Army fuel problems are underreported, because a high proportion of fuels that fail to meet the specification must cause problems.

The Army could reduce diesel fuel specification failures by instituting more-thorough acceptance procedures and it could also increase diesel fuel quality for the end user by installing filter separators at more installations. Those steps are unlikely to be cost-effective if the first hypothesis is valid, and they might not be cost-effective even if the second hypothesis is valid.

ARE CRUDE OIL AND REFINING TRENDS LEADING TO LOWER-QUALITY FUELS?

We examined changes in crude oils and changes in refinery operations in order to assess the effects that decreasing crude oil quality and increasing refinery conversion have on product quality. Data on crude oils refined in the United States show that two crude oil properties — API gravity (density) and sulfur content — worsened in the recent past mainly because of increased use of heavier imported crude oils. Worldwide crude oil quality does not appear to be worsening, however. The effect of crude oil changes in the United States on fuel quality has been mixed. Lower crude oil quality may have contributed to some observed product-quality declines, but increased crude oil sulfur content has not translated into higher sulfur levels in DoD fuels.

Heavier crude oils can lead to increased reliance on conversion processes in refining (or vice-versa, increased investment in conversion capacity can lead refiners to purchase heavier crude oils), which can reduce fuel quality. Since 1970, however, U.S. conversion capacity has grown only slowly. In addition, refining severity — the utilization of conversion capacity— has not changed significantly over the past 15 years. An exception, increased use of the coking conversion process, affects a relatively small portion of petroleum fuels but could result in lower-quality diesel fuels. Finally, evidence on planned domestic refinery construction does not lead us to expect a sharp increase in conversion capacity in the near future.

Crude Oil Quality Trends

Data on crude oil quality changes are limited.[1] Available data on crude oils refined in the U.S. shows that sulfur content and API gravity (a measure of density or weight) both became worse between 1978 and 1985 [4-3].[2] Those trends are summarized by the lines labeled "Total U.S. Crude Oil" in Figures 4-1 and 4-2. We cannot infer from those trends, however, that higher-quality crudes are becoming unavailable. U.S. crude oil quality declined largely because of changes in imported crude oil; the properties of domestically produced crude oils changed relatively little in that period. Since oil producers outside the U.S. have excess production capacity and could supply higher-quality (and more expensive) imported crude oils if refinery economics warranted, past declines do not mean that continued declines are inevitable.

Lower-quality crude oil does not invariably result in lower-quality fuels. For example, higher crude oil sulfur levels have not translated into higher sulfur levels in DoD fuels. Figure 4-1 illustrates that the sulfur content of F-76 improved and that of both JP-4 and JP-5 remained virtually unchanged at the same time that crude oil sulfur was getting worse. That is, U.S. refiners were generally able to compensate for lower-quality crude oils and maintain, or even improve, product quality.

Heavier crude oils can, in principle, reduce diesel fuel ignition quality (cetane number) because they tend to contain a higher proportion of aromatic compounds [4-3]. Figure 4-2 shows that, during the period when the API gravity of U.S. refined crude oil decreased, the cetane number of commercial diesel fuels did not decline although the cetane number of F-76 did. The main effect of refining heavier crude oils, however, is to reduce the amount of commercially valuable "light" products such as gasoline and diesel fuel that can be produced by "simple" refineries, and therefore increase the need for refinery conversion (asuming that light product demand is constant or increasing). In fact, increased conversion capacity is probably the cause rather than the result of the increased API gravity of U.S. refined crude oil (see Appendix B). Heavier crude oils are cheaper than higher-quality crude oils and have

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[1]Reliable data do not exist on worldwide crude oil quality trends because data for a number of major oil-producing nations are limited to total production rates.However, one estimate shows API gravity declining from 33.7 in 1975 to 33.5 in 1980, an extremely small change [4-2].

[2]Some of the data prior to 1982 are estimated.

Sulfur content
(wt %)

Total U.S. crude oil

1.0

F-76

0.5

JP-5

JP-4

0.0

1977   1979   1981   1983   1985

Year
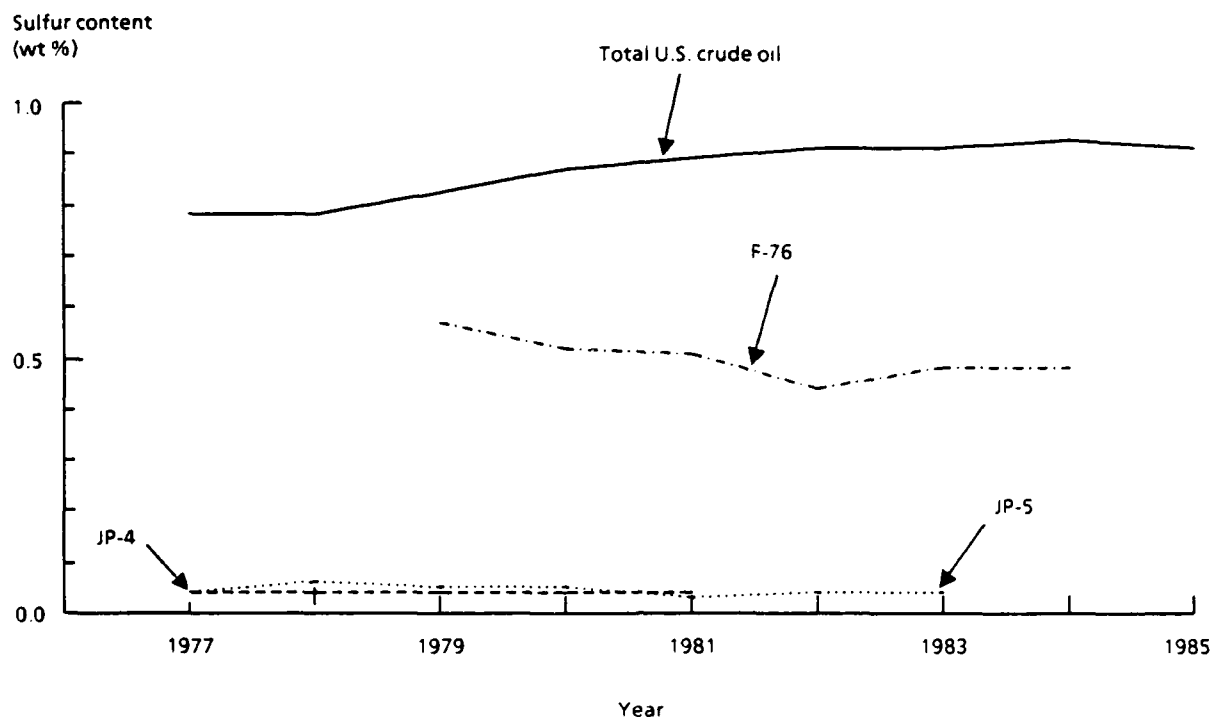
Sources: NIPER, Air Force, and Navy.

FIG. 4-1. CRUDE OIL SULFUR TRENDS VERSUS MILITARY FUEL SULFUR TRENDS

a greater potential for conversion into light products. U.S. refiners, who have larger investments in conversion capacity than overseas refiners, tend to buy heavier crude oils in order to profit from those investments. Overseas refiners are limited to the use of higher-quality crude oils because they have less conversion equipment. To measure the full effect of heavier crudes on product quality, therefore, we must examine changes in refinery conversion capacity and use.

Refinery Conversion Trends

Increased refinery conversion, as discussed in Chapter 2, has the potential to reduce product quality. For example, catalytic cracking can directly reduce diesel fuel cetane number [2-3]. Refinery conversion can also reduce storage and thermal stability (see Appendix C). Conversion processes generally decrease fuel stability by changing the chemistry of fuels and increasing the concentration of relatively unstable compounds. Of the three conversion processes, thermal conversion processes are generally the worst in this regard, followed by catalytic cracking and then hydrocracking processes. Straight-run fuels are the most stable.

Cetane number

API Gravity

Sources: NIPER and Navy

Year
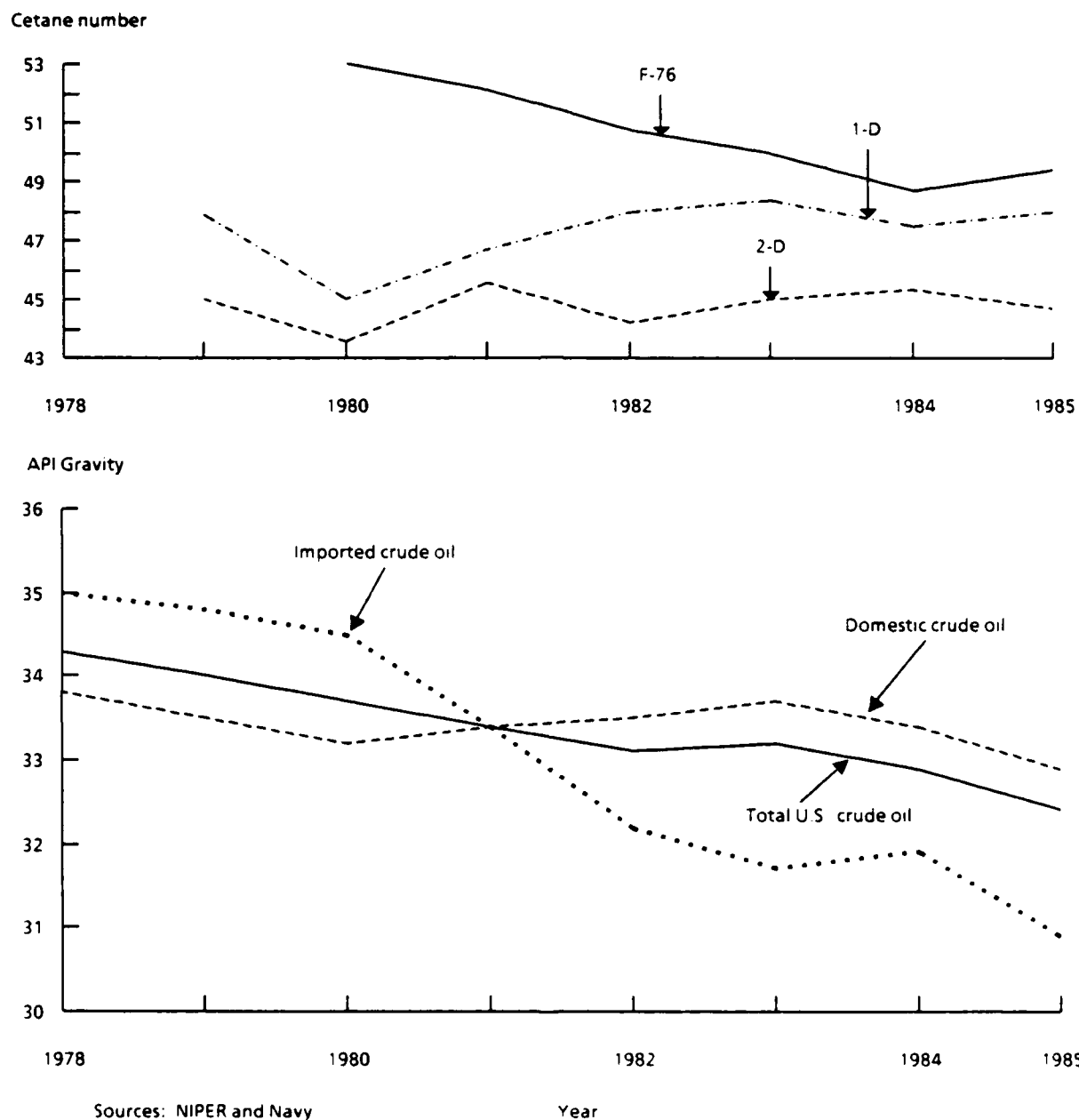
FIG. 4-2. CRUDE OIL GRAVITY VERSUS DIESEL FUEL IGNITION QUALITY

We concentrated on changes in domestic refining capacity for three reasons, (1) the U.S. refining industry uses more conversion capacity than any other country,[3] (2) U.S. refineries supply about two-thirds of DoD fuels, and (3) military

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[3]Western European catalytic cracking capacity in 1986 was 12 percent of total refining capacity, compared with 33 percent in the United States [4-4].

fuels in Europe are moving increasingly toward a JP-8 standard, which has a very small cracked component.

The capacity of conversion processes in U.S. refineries has not significantly increased since 1970 [4-5]. Absolute and relative conversion capacities are shown in Figure 4-3. The absolute level of U.S. conversion capacity has grown rather slowly over the past decade, but as a percent of total refining capacity, current conversion capacity is relatively unchanged from the 1970 level. Catalytic and thermal cracking capacities, as a percent of total capacity, have actually declined from their 1970 levels. Catalytic cracking is the major conversion process available in the United States, followed by thermal cracking, then hydrocracking.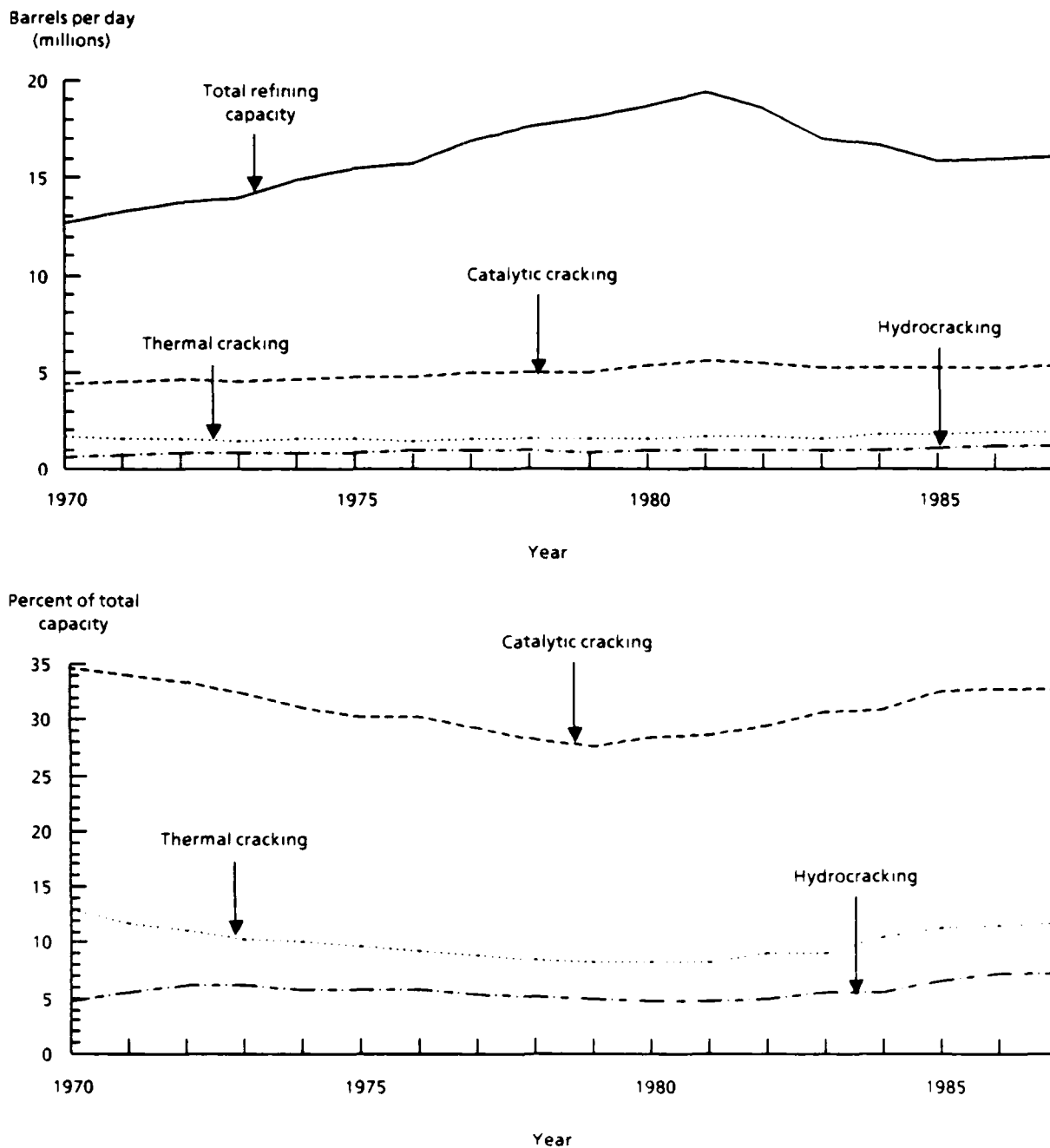 The pattern of rise and fall in relative refining capacity largely reflects the increase in simple distillation capacity that resulted from the 1970s crude oil entitlements program. Refineries that had only simple distillation capacity (and no conversion) became uneconomic after crude oil was deregulated in 1980, and total U.S. distillation capacity therefore decreased.

The "severity," or rate of use, of domestic conversion capacity has remained relatively steady. That is, idle conversion capacity has not decreased significantly nor have conversion processes been run at higher severities to produce higher rates of conversion. One way of measuring conversion severity, as distinct from capacity, is to measure refinery gain. Since distillation is a physical process, output volume should roughly equal input volume (in fact, output volume is usually slightly lower because of processing losses). All conversion processes, on the other hand, cause chemical changes that increase the volume of the final products, and that increase is known as refinery gain. Product weight is unchanged but volume increases as heavy products are converted into light products. The pattern of refinery utilization as measured by refinery gain is shown in Figure 4-4 [4-6] and mirrors the capacity changes shown in Figure 4-3. That is, overall conversion severity was about the same in 1985 as it was in 1973. This confirms the conclusion that the degree of refinery conversion has not changed significantly in the past 15 or so years.

There is one exception, however. Refiners appear to be processing the bottom of the barrel more intensively than before. Coking is a thermal cracking process that totally converts residual fuel oil into lighter products. A by-product of the coking process is pure carbon in the form of marketable coke. Since marketable coke is produced only from the coking process, coke production is a direct measure of the

Barrels per day (millions)

Total refining capacity

Thermal cracking

Catalytic cracking

Hydrocracking

1970   1975   1980   1985

Year

Percent of total capacity

Catalytic cracking

Thermal cracking

Hydrocracking

1970   1975   1980   1985

Year

Source: Oil and Gas Journal [4-5]

FIG. 4-3. U.S. REFINERY CONVERSION CAPACITY TRENDS

degree of conversion accomplished by coking. Coke production per barrel of refinery output increased by 64 percent between 1973 and 1985 (from 6.5 pounds/barrel to 10.7 pounds/barrel, as shown in Figure 4-5) despite only an 11 percent increase in thermal cracking capacity [4-5, 4-6], indicating increased utilization rates (as well,

possibly, as a decrease in other thermal cracking processes). As mentioned previously, thermal cracking processes, which include coking, tend to decrease product stability even more than catalytic cracking. (Coking makes up a portion of the total thermal cracking capacity shown in Figure 4-3).

Percent volume
expansion (gain)

Year

FIG. 4-4. OVERALL U.S. CONVERSION SEVERITY

Having examined past trends, we must next look at the question of the future of refinery conversion. The evidence does not point to a significant increase in domestic conversion capacity in the near future. The recent increase in conversion capacity slowed down between 1985 and 1987. In addition, the number of new refinery units currently under construction or planned indicates that domestic conversion capacity is unlikely to grow significantly over the remainder of this decade [4-7]. Figure 4-6 forecasts domestic conversion capacity through 1990. Refinery conversion units are generally expensive and require considerable leadtime to design and construct. Moreover, they are risky investments, given the recent volatility of petroleum markets. Past changes in the extent of refinery conversion have been gradual, and no evidence indicates that the future will be any different.

None of the conversion processes used by refiners today are new technologies. Catalytic cracking was developed on a commercial scale during World War II, and while further developments have taken place, they have been evolutionary rather than radical. Today's conversion technology uses more-sophisticated catalysts and other refinements but has remained unchanged in its essentials for many years.

Pounds Per
Barrel

Year
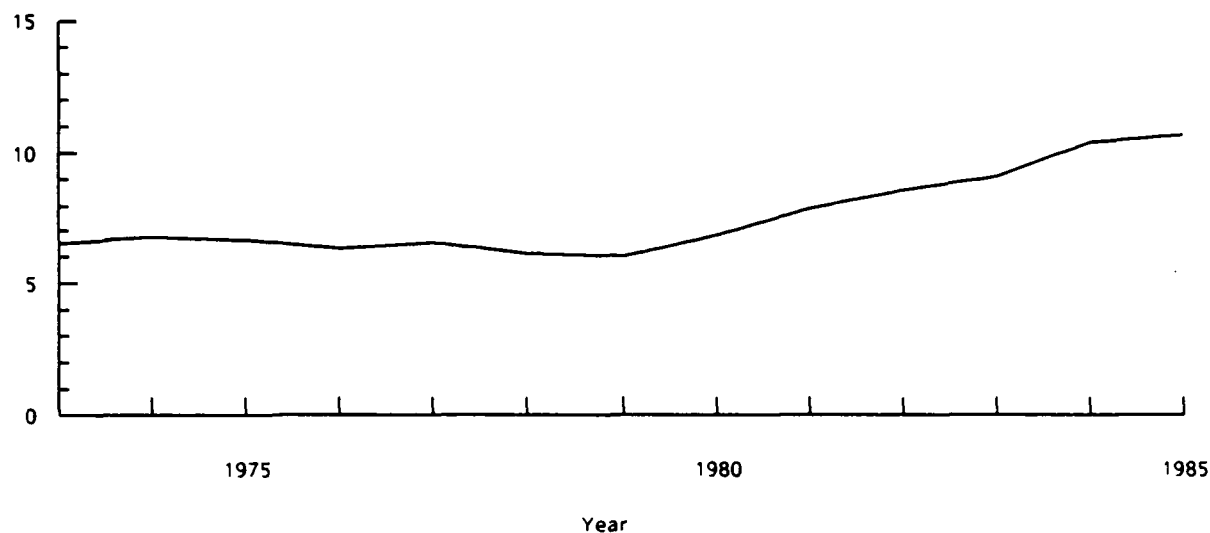
Source: Oil and Gas Journal [4-5]; Monthly Energy Review [4-6].

FIG. 4-5. U.S. COKING SEVERITY AS MEASURED BY COKE PRODUCTION

Year
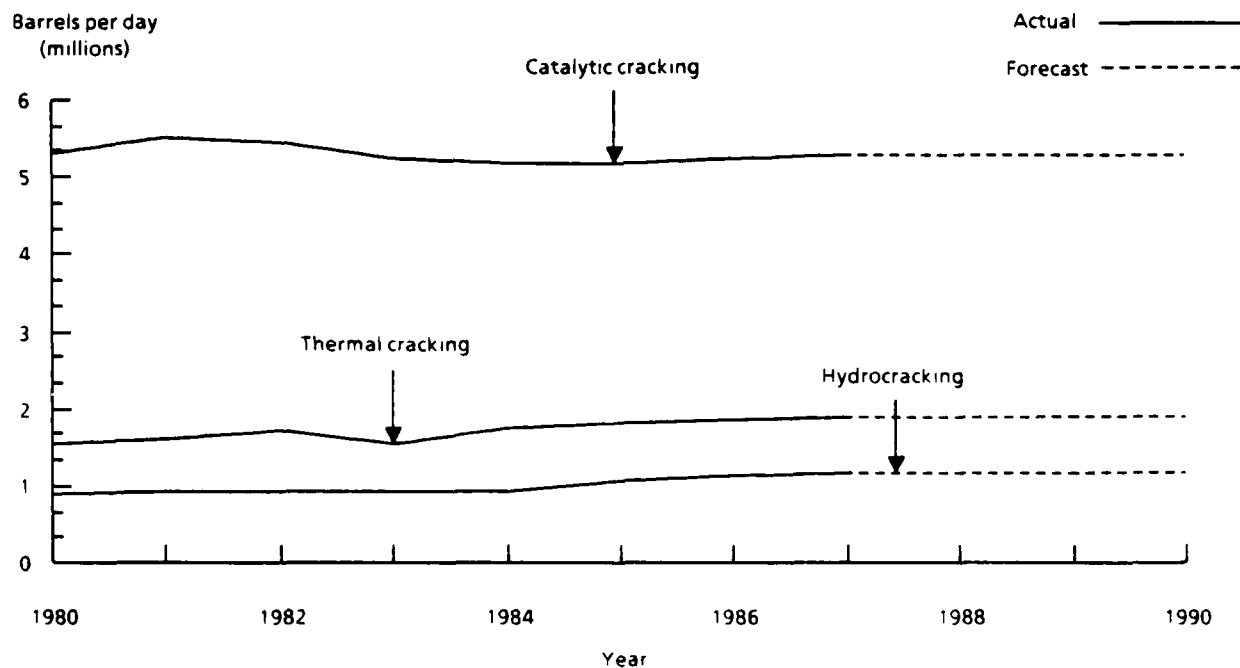
Source: Oil and Gas Journal. [4-5, 4-7]

FIG. 4-6. RECENT AND FUTURE U.S. CONVERSION CAPACITY TRENDS

Domestic refinery conversion has undergone no radical changes; on the contrary, refinery conversion capacity as a percentage of total capacity is roughly at the same level now as it was in the early 1970s. Furthermore, conversion capacity is not expected to accelerate since relatively few new units are planned for the near future.

Moreover, DoD does not yet have to worry about an inevitable decline in the quality of crude oils beyond the ability of refiners to process them since worldwide production overcapacity means that high-quality crude oils are available from accessible locations, such as the North Sea. DoD needs to worry even less about the possible effects on product quality of synthetic crude oils since their use will probably remain uneconomic for many more years.

Nevertheless, DoD should remain alert to product quality trends. Some changes in U.S. refinery processing have occurred; coking, in particular, has increased over the past 12 years, and since it is a severe thermal cracking process, it can result in lower fuel stability. Diesel fuels have experienced more quality declines than have jet fuels, possibly as a result of increased catalytic and thermal cracking between about 1980 and 1985. (Refiners do not use catalytic cracking and thermal cracking processes to make jet fuel because of the specification limits on olefin content.)

CHAPTER 5

MANAGING FUEL INSTABILITY

We conclude that DoD has relatively few fuel problems compared with the large volume of fuels that it annually purchases, stores, and uses. Nevertheless, DoD's fuels logistics system continues to face some fuel instability problems. In this chapter, we discuss those problems and ways of overcoming them.

CAUSES OF INSTABILITY

Storage instability affects only a relatively small percentage of DoD fuels because most DoD fuels turn over relatively rapidly and, like most commercial fuels, simply do not have time to deteriorate. High turnover is also accompanied by frequent commingling of various batches of fuel with the result that potential problem batches are normally diluted to such an extent that problems never appear. The DoD fuels most susceptible to major storage stability problems are diesel fuels in dormant (long-term) storage, such as those in war reserves in low-turnover areas overseas.

Causes of fuel instability include refining processes and/or storage and handling practices, but there is no simple relation between cause and effect. For example, it is not yet possible to predict the storage stability of a particular fuel based only on the processes used to manufacture that fuel; refinery conversion processes do not invariably produce unstable fuel. The degree of instability depends on many factors including the chemistry of the original crude oil and product storage conditions. Naval fuels researchers, attempting to reproduce storage stability problems, have purchased fuels containing a high proportion of catalytically cracked stock only to have those fuels remain stubbornly within specification.

TESTING FOR INSTABILITY

Many accelerated stability (or accelerated aging) tests have been developed in an attempt to predict the storage stability of petroleum fuels. An effective stability test would allow a purchaser to accept or reject a batch of fuel based on an accurate prediction of the fuel's future storage stability. Such a test would reduce the need for

actively managing fuel stability in the fuels logistics system because the test would reject most batches of potentially unstable fuel. The ideal test would be reliable, reproducible, and administratively feasible. A reliable test of accelerated stability is one that can predict whether fuel will deteriorate over time. An effective test should also be reproducible; it should not be possible for test results to vary widely from laboratory to laboratory or technician to technician. In addition, an administratively feasible test is one that can be performed quickly; this characteristic is necessary for routine use as part of a fuel specification.

None of the existing accelerated stability tests meets all the criteria just described. One such test is reliable and reproducible but impractical for use in acquiring and monitoring fuels; the test that is used by DoD shows poor reproducibility and cannot reliably predict the storage stability of a given batch of fuel. DoD researchers are currently searching for a more effective stability test.

A fuel storage program carried out by the Navy and the Coordinating Research Council in the 1950s first showed a strong correlation between the effects of storage at 110° F and the effects of long-term storage [2-1]. With the accumulation of additional evidence since then, most researchers have judged that test to be reproducible and reliable and have accepted its validity. However, the 110° F test requires that the fuel be stored for 13 weeks. Since the test cannot be performed quickly, it is impractical for use in acquiring and monitoring fuels.

Accelerated tests that can be performed quickly tend to be unreliable because the higher temperatures that are needed to simulate long-term storage usually produce additional chemical reactions that do not normally occur at actual storage temperatures. According to Army-sponsored research, ". . . absolute test methods for predicting fuel quality at specific time intervals, under all types of storage conditions, have yet to be developed." [5-1]

DoD's diesel fuel specifications include the American Society for Testing and Materials (ASTM) accelerated test for diesel fuel (ASTM D 2274).[1] Unfortunately, both research and experience have demonstrated that this test fails to show a significant correlation with the actual storage behavior of distillate fuel. That is, it

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[1]ASTM is currently reviewing two additional stability tests: a 3-month dark storage test and a 90-minute, 300° F test (a modified version of the DuPont F21-61 test) [2-2]. The former is obviously impractical as a purchasing test, and the latter is an unreliable predictor of fuel stability.

is unable to predict reliably the sediment-forming potential of a particular batch of diesel fuel during storage. A British study of fuel stability mechanisms and stability tests states that, " . . . the results of such tests [including ASTM D 2274] show little or no relation to those of fuels which have been stored under ambient conditions" [5-2].

Researchers at the David Taylor Naval Ship Research and Development Center have attempted to correlate the results of various accelerated stability tests with the behavior of fuel in long-term storage [5-3]. They found, however, that the results of ASTM Method D 2274 did not show a statistically significant relationship with the levels of sediment formed under actual storage conditions. They stated, "Efforts to relate the results of ASTM Method D 2274 accelerated stability tests to the results of beaker and bottle storage were disappointing. Interim data had indicated the possibility of such relationships, but the 30- and 36-month bottle storage data tended to show a decrease of total insolubles in the bottles associated with an increase in the total insolubles produced in D 2274 tests." Similarly, Army-sponsored research has found that ASTM Method D 2274 does not predict results of the 110°F test, which correlates very well with actual storage results [5-4].

Experience has also revealed the inadequacy of the ASTM D 2274 test. The Navy recently purchased a 250,000 gallon batch of F-76 fuel for research purposes. The fuel met the F-76 specification plus some additional requirements (lower sulfur content and higher cetane number). Despite this, the fuel's color and particulate content rose above the specification limits after only 6 months in isolated storage aboard a barge. Reporting on this occurrence, Naval researchers concluded that the F-76 fuel specification "is not adequate to protect against the receipt of a fuel which can develop a stability problem" [5-5]. Furthermore, despite use of the test, DFSC and the Army continue to experience storage stability problems.

In addition to the poor correlation of the D 2274 test results with actual storage results, the test shows poor reproducibility. In other words, two technicians working from an identical sample can obtain significantly different test results [5-6].

MANAGING INSTABILITY IN THE LOGISTICS SYSTEM

Since an effective fuel stability test has yet to be developed, fuels logisticians must use other methods to ensure the reliability of their fuels during long-term storage. Long-term storage does not inevitably lead to fuel deterioration. In many

cases, DoD and NATO fuels have been stored for years without problems. Other nations also store fuels successfully for long periods. The Swiss and the Israelis, for example, reduce the possibility of deterioration in stored diesel fuel by specifying straight-run, hydrotreated diesel fuel. They also test their stored fuels regularly since no specification can totally eliminate the possibility of deterioration. The Swiss have successfully stored diesel fuel for periods exceeding 10 years [5-7]. They test the fuel after the first 3 years and subsequently every second year. In addition, Switzerland, Sweden, Norway, and South Africa maintain large stocks of fuels in underground storage. Sweden and Norway use unlined rock caverns, and South Africa uses lined underground tanks. As Israeli fuels researchers have stated, "The utilization of underground space for the storage of fuel is a very attractive option due to safety, security, environmental and economic considerations" [5-8].

Additives have also proved effective in preventing and curing fuel stability problems in some cases. No single additive can be universally effective, however, because stability problems have many causes. In general, stability additives work best when injected into the fuel as soon as possible after refining before the various instability mechanisms have had a chance to go to work.

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APPENDIX A

FUEL PROPERTY CHANGES

This appendix describes the methods we used to analyze fuel property changes. The results and the significance of our analysis are discussed in Chapter 3.

Two sets of data are available to measure JP-4 fuel property changes over time, and another two sets of data measure JP-5 fuel property changes. One set of data measures F-76 fuel property changes. One set of data measures changes in Army diesel fuel, and one set measures changes in commercial diesel fuels. The strengths and drawbacks of these seven data sources are summarized below:

JP-4

1. Source: Air Force [A-1].
    Period covered: 1960 through 1981 (some 1970 through 1981).
    Number of samples: About 65 percent of all fuels purchased.
    Number of properties tracked: 19.
    Data: Graphs of annual averages (numbers given only for 1980 and 1981).

2. Source: National Institute for Petroleum and Energy Research (NIPER) [A-2].
    Period covered: 1974 through 1984.
    Number of samples: 23 to 33.
    Number of properties tracked: 18.
    Data: Annual averages.

JP-5

1. Source: Navy [A-3].
    Period covered: 1977 through 1983. Number of samples: All fuels purchased.
    Number of samples: All fuels purchased.
    Number of properties tracked: 33.
    Data: Annual averages and frequency distributions.

2. Source: NIPER [A-2].
    Period covered: 1974 through 1984.
    Number of samples: 5 to 8.
    Number of properties tracked: 17.
    Data: Annual averages.

F-76

1.   Source: Navy [A-4].[1]
      Period covered: 1979 through 1984.
      Number of samples: All fuels purchased.
      Number of properties tracked: 18.
      Data: Annual averages and standard deviations.

ARMY DIESEL FUELS (DF-A, DF-1, AND DF-2)

1.   Source: Army.
      Period covered: 1984 – 1986.
      Number of samples: All fuels tested (about 8 percent of all fuels purchased).
      Number of properties tracked: 10.
      Data: Available upon request.

COMMERCIAL DIESEL FUELS

1.   Source: NIPER [A-5].
      Period covered: 1970 through 1985.
      Number of samples: Approximately 200 per year.
      Number of properties tracked: 12-14.
      Data: Annual averages.

The main drawback of the NIPER JP-5 data set is the lack of samples; it includes too few samples to evaluate. The Army data cover only 3 years and so we did not use them (GMPA can supply annual averages if desired). NIPER reported annual averages for "Type City Bus" fuel and "Type Truck-Tractor" fuel until 1982 but stopped reporting on those two fuels in favor of reporting on diesel fuel Types 1-D and 2-D. (Some data for 1-D and 2-D fuels were reported starting in 1979, other data are available only from 1981.)

Few yearly averages remained constant over the periods measured, but the changes were not necessarily statistically significant. That is, relatively few property changes could be correlated with time. We applied the ordinary least-squares regression technique to determine whether a change was statistically significant. We estimated an equation of the following form: FUEL PROPERTY = C + [B x (YEAR)] + E, where C is a constant, or intercept, B is a coefficient that estimates the marginal change in the fuel property per year (the slope), and E is an error term to measure the unexplained variation in fuel properties over time. If the

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[1]The data in reference [A-4] were updated for this study by N.F. Lynn of the David Taylor Naval Ship Research and Development Center, Annapolis, MD.

coefficient B (the slope) in the regression equation passed a statistical test of significance (i.e., the "T-statistic" was 2.0 or greater), we judged the property change to be significant. A T-statistic of 2.0 or more indicates that the probability is less than 0.05 that the estimated coefficient was obtained purely by chance. If the slope was negative, the property declined, and if positive, it increased. Whether the change was better or worse depended on the specification limit; a decrease is an improvement if the specification is a maximum, deterioration if the specification is a minimum.

Tables A-1 and A-2 summarize the regression results for military jet and diesel fuels as well as four commercial diesel fuels. The first column shows the fuel properties measured by the various data sets. The last columns indicate whether the property got worse, better, or remained the same. A blank indicates that the property was not included in the data set.

Tables A-3 and A-4 summarize the fuel properties that worsened by comparing the marginal change per year (the slope) determined by the regression analysis with actual measured property values and the specification limit. Few of the fuel properties approached their limits. For example, the flash point of 1-D commercial diesel fuel (Table A-4) declined during the period 1981 through 1985. The marginal change was -1.0°F per year, and the average value in 1985 was 135°F compared with a specification of 100°F.

Finally, Tables A-5 through A-9 detail the regression results, including the marginal change per year (the slope), the T-statistic of the slope, and the correlation coefficient (R^2) for the regression equation. R^2 indicates the extent to which the property change correlated with time.

TABLE A-1

CHANGES IN MILITARY JET FUEL PROPERTIES OVER TIME

Fuel properties	JP-4		JP-5
	Air Force (1960-1981)	NIPER (1974-1984)	Navy (1977-1983)
Smoke Point	Worse	Worse	Same
Aromatics	Same	Worse	Worse
WSIM	Same	Same	Worse
Freeze Point		Worse	Same
Peroxides			Worse
Distillation, loss (D86)d			Worse
Water tolerance, ml		Worsec	
Total sulfur	Better	Better	Same
Mercaptan sulfur	Same	Better	Same
Olefins	Better	Same	Same
Particulates	Bettera		Same
Acid number	Bettera		Same
Flash point			Better
Distillation, 10% (D86)d	Samec	Betterc	Same
Distillation, 20% (D86)	Better		Samec
Distillation, 50% (D86)	Better	Same	Samec
Distillation, FBP (D86)	Better		Same
Distillation, 10% (D2887)d			Better
Distillation, 20% (D2887)			Betterc
Distillation, 50% (D2887)			Betterc
API gravity	Same	Same	Same
Pressure drop	Sameb	Same	Same
Gum	Same	Same	Same
Aniline-gravity product		Same	Same
Aniline point, deg F		Samec	
Heat of combustion	Samea	Same	
Reid vapor pressure	Same	Same	
Viscosity, 20 deg C			Same
Explosiveness			Same
Preheater deposit code			Same
Viscosity, 30 deg C			Samec
Distillation, IBP (D86)d	Samec		Same
Distillation, 90% (D86)	Same	Same	Samec
Distillation, residue (D86)			Same
Distillation, IBP (D2887)d			Samec
Distillation, 90% (D2887)			Samec
Distillation, FBP (D2887)			Same

' 1970 - 1981

b An apparent improvement was due to a change in the test method

c Property limit not included in product specification

d D86 and D2887 refer to two alternative distillation methods

TABLE A-2

CHANGES IN DIESEL FUEL PROPERTIES OVER TIME

Fuel properties	F-76 (1979-1984)	City Bus (1970-1982)	1-D (1981-1985)	Truck-Tractor (1970-1982)	2-D (1981-1985)
Aniline point	Worse[a]	Worse	Worse	Worse	Worse
Cetane number	Worse	Worse	Same[b]	Worse	Same[b]
API gravity	Worse[a]	Same	Same	Worse	Same
Viscosity	Worse	Same	Same[b]	Same	Same[b]
Pour point	Worse				
Cloud point	Worse				
Distillation, IBP		Worse	Same	Worse	Same
Distillation, 50%	Worse[a]	Same	Same	Same	Same
Distillation, 90%	Same	Same	Same[b]	Worse	Same[b]
Distillation, FBP	Same	Same	Same[b]	Worse	Same[b]
Total sulfur	Better	Worse	Worse[b]	Same	Same[b]
Flash point	Better		Worse		Same
Ash	Same	Same	Same	Same	Same
Carbon residue	Same	Same	Same	Same	Same
Cetane Index			Same		Same
Accelerated stability	Same				
Demulsification	Same				
Acid number	Same				
Water & sediment	Same				
Distillation, 10%		Same	Same[b]	Same	Same[b]
Distillation, residue & loss	Same				

[a] Property limit not included in military product specification.

[b] 1979 – 1985.

TABLE A-3

MILITARY FUEL PROPERTIES THAT WORSENED

(JP-4, JP-5, and F-76)

Property	Units	Marginal change per year (slope)	Actual annual averages		Current specification
			First data year	Last data year	
JP-4 (Air Force data):			1960	1981	
Smoke point, MIN	mm	(0.081)	28.8	26.9	20.0
JP-4 (NIPER data):			1974	1984	
Smoke point, MIN	mm	(0.267)	28.1	25.7	20.0
Freeze point, MAX	deg F	0.636	(−81)	(−79)	(−72)
Aromatics, MAX	% vol	0.171	10.6	12.1	25.0
Water tolerance	ml	0 024	0.5	0.6	None
JP-5 (Navy data):			1977	1983	
WSIM, MIN	WSIM	(1 607)	93	86	85/70[a]
Peroxides, MAX	meq/kg	0.052	0.13	0 35	1 0
Aromatics, MAX	% vol	0.146	18.1	19 0	25 0
Distillation loss (D86), MAX	% vol	0.016	0.80	0 88	1 5
F-76 (Navy data):			1979	1984	
Distillation, 50%	deg C	1 771	272	281	Record[b]
API gravity	deg API	(0 400)	36 1	34 3	Record[b]
Cetane number, MIN	no	(0 829)	53 0	49 4	45
Aniline point	deg C	(0 649)	68 6	65 0	None
Viscosity, MIN/MAX	cSt	0 046	3 19	3 43	1 7 − 4 3
Distillation, 90% MAX	deg C	0 829	330	334	357
Cloud point, MAX	deg C	0 229	(−7)	(−6)	(−1)
Pour point, MAX	deg C	0 229	(−12)	(−11)	(−6)

a With/without additives.

b Property must be measured and recorded but no limit is included in specification.

TABLE A-4

COMMERCIAL DIESEL FUEL PROPERTIES THAT WORSENED

Property	Units	Marginal change per year (slope)	Actual annual averages		Comparable military specification
			First data year	Last data year	
City Bus (NIPER data)			1970	1982	
Cetane number	no	(0 345)	50.0	46.7	40
Aniline point	deg F	(0.344)	148.2	145.1	None
Distillation, IBP	deg F	0.488	348	353	None
Sulfur content	% wt	0.002	0.100	0.118	0.50
1-D (NIPER data)			1981	1985	
Flash	deg F	(1 000)	138	135	100
Aniline point	deg F	(0 500)	145 2	143 4	None
Sulfur content	% wt	0 004	0.070[a]	0 094	0 50
Truck-Tractor (NIPER data)			1970	1982	
Aniline point	deg F	(0 253)	147.1	143.5	None
Cetane number	no	(0 322)	48 6	44 7	40
Distillation, FBP	deg F	0 980	615	630	698
Distillation, 90%	deg F	0 537	571	583	675
Ash	% wt	0 000	0 0010	0.0017	0 01
API gravity	deg API	(0 053)	36 5	35.6	Record[b]
Distillation, IBP	deg F	0 362	372	378	None

a 1979 average

b Density (kg/L) must be measured and recorded but no limit is included in specification (API gravity is an alternate measure of density).

TABLE A-5

JP-4 REGRESSION RESULTS

Property (dependent variable)	Units	Marginal change per year (slope)	T-Statistic of slope	Correlation with time (R^2)	Better, worse, or same
Air Force data					
Significant change					
Total sulfur	% wt	(0.001)	(6.4)	85.5%	Better
Distillation, 20% (D86)	deg F	(0.550)	(5.2)	79.5%	Better
Olefins	% vol	(0.013)	(4.4)	73.1%	Better
Smoke point	mm	(0.081)	(3.2)	77.3%	Worse
Particulates	mg/L	(0.003)	(3.1)	76.8%	Better
Acid number	mg KOH/g	(0.000)	(3.1)	76.8%	Better
Pressure drop	mm Hg	(0.378)	(2.6)	58.1%	Same[a]
Distillation, 50% (D86)	deg F	(0.514)	(2.3)	43.2%	Better
Distillation, FBP (D86)	deg F	(0.630)	(2.1)	39.2%	Better
Insignificant change:					
Heat of combustion	Btu/lb	(2.467)	(1.9)	55.8%	Same
Distillation, IBP (D86)	deg F	(0.123)	(1.9)	33.0%	Same
API gravity	deg API	0.034	1.8	30.9%	Same
Distillation, 10% (D86)	deg F	(0.315)	(1.2)	31.5%	Same
WSIM	WSIM	(0.155)	(1.1)	27.8%	Same
Aromatics	% vol	0.030	0.9	10.9%	Same
Distillation, 90% (D86)	deg F	(0.304)	(0.8)	8.6%	Same
Reid vapor pressure	lbs Reid	0.001	0.7	5.9%	Same
Mercaptan sulfur	% wt	(0.000)	(0.6)	5.6%	Same
Gum	mg/100 ml	(0.003)	(0.6)	5.2%	Same
NIPER data					
Significant change:					
Distillation, 10% (D86)	deg F	(2.136)	(6.6)	82.7%	Better
Smoke point	mm	(0.267)	(5.4)	76.7%	Worse
Total sulfur	% wt	(0.002)	(4.7)	71.5%	Better
Freeze point	deg F	0.636	3.2	52.6%	Worse
Mercaptan sulfur	% wt	(0.000)	(2.7)	44.6%	Better
Aromatics	% vol	0.171	2.4	39.8%	Worse
Water tolerance	ml	0.024	2.2	34.1%	Worse
Insignificant change:					
Distillation, 50% (D86)	deg F	(1.064)	(1.9)	28.4%	Same
Aniline point	deg F	(0.266)	(1.8)	27.1%	Same
Pressure drop	inches Hg	(0.024)	(1.7)	24.8%	Same
WSIM	WSIM	(0.127)	(1.2)	14.0%	Same
API gravity	deg API	0.036	1.1	11.0%	Same
Gum	mg/100 ml	0.010	0.9	7.8%	Same
Aniline-gravity product	No	(9.618)	(0.8)	7.0%	same
Olefins	% vol	(0.007)	(0.8)	6.0%	Same
Heat of combustion	Btu/lb	(0.627)	(0.5)	3.1%	Same
Reid vapor pressure	psi	0.002	0.3	1.3%	Same
Distillation, 90% (D86)	deg F	0.209	0.3	0.8%	Same

[a] The apparent improvement was due to a change in test method

TABLE A-6

JP-5 REGRESSION RESULTS

Property (dependent variable)	Units	Marginal change per year (siope)	T-Statistic of slope	Correlation with time (R²)	Better, worse, or same
Significant change:					
WSIM	WSIM	(1.607)	(4 8)	82 5%	Worse
Peroxides	meq/kg	0 052	3 9	75.6%	Worse
Aromatics	% vol	0 146	3 3	69.1%	Worse
Distillation, 20% (D2887)	deg C	(0.821)	(3 1)	65.5%	Better
Distillation, 50% (D2887)	deg C	(1 179)	(2.9)	63.0%	Better
Distillation loss (D86)	deg C	0 016	2.7	59.9%	Worse
Flash point	deg C	0.393	2 4	54.0%	Better
Distillation, 10% (D2887)	deg C	(0.857)	(2.0)	45.3%	Better
Insignificant change:					
Viscosity, 20 degrees C	cSt	(0.125)	(1 9)	41.6%	Same
Particulates	mg/L	0.005	1 7	37.5%	Same
Explosiveness	%	(0.357)	(1.5)	31.3%	Same
Aniline-gravity product	MJ/kg	(17 071)	(1.5)	30.6%	Same
Total sulfur	% wt	(0.002)	(1.2)	22.5%	Same
Distillation, FBP (D2887)	deg C	0.786	1.1	20.7%	Same
Viscosity, 30 degrees C	cSt	(0.100)	(1 1)	19.9%	Same
Distillation, IBP (D2887)	deg C	1 036	1.1	19.5%	Same
Smoke point	mm	(0.054)	(1.0)	17.1%	Same
Mercaptan sulfur	% wt	0.000	(1 0)	16.7%	Same
Distillation, 10% (D86)	deg C	(0.179)	(1 0)	15.6%	Same
Distillation residue (D86)	% vol	(0.003)	(0.9)	13.1%	Same
Distillation, 20% (D86)	deg C	(0.107)	(0 8)	11.3%	Same
Freeze point	deg C	(0 100)	(0 7)	10.0%	Same
Olefins	% vol	(0 018)	(0 7)	9.5%	Same
Distillation, FBP (D86)	deg C	(0 286)	(0 6)	7 2%	Same
API gravity	deg API	(0.025)	(0 4)	3 4%	Same
Gum	mg/100 ml	0 006	0 4	3 1%	Same
Acid number	mg KOH/g	0 000	0 4	2 5%	Same
Distillation, 90% (D2887)	deg C	(0 143)	(0 4)	2 4%	Same
Distillation, IBP (D86)	deg C	0.071	0 3	1 4%	Same
Distillation, 50% (D86)	deg C	0 036	0 3	1 3%	Same
Distillation, 90% (D86)	deg C	(0 071)	(0 2)	1 1%	Same
Pressure drop	mm of Hg	0.000	0 0	–	Same
Preheater deposit code	No.	0.000	0.0	–	Same

TABLE A-7

F-76 REGRESSION RESULTS

Property (dependent variable)	Units	Marginal change per year (slope)	T-Statistic of slope	Correlation with time (R^2)	Better, worse, or same
Significant change:					
Distillation, 50%	deg C	1.771	14.2	98.1%	Worse
API Gravity	deg API	(0.400)	(8.4)	94.6%	Worse
Cetane number	No.	(0.829)	(5.8)	89.4%	Worse
Flash point	deg C	0.943	5 7	88.9%	Better
Aniline point	deg C	(0.649)	(4.7)	84.7%	Worse
Viscosity	cSt	0.046	3.4	74.3%	Worse
Distillation, 90%	deg C	0.829	3 2	71.4%	Worse
Cloud point	deg C	0.229	3 0	68.6%	Worse
Pour point	deg C	0.229	3 0	68.6%	Worse
Sulfur content	% wt	(0.018)	2.4	59.7%	Better
Insignificant change:					
Water & sediment	% vol	0.000	1 9	47.0%	Same
Carbon residue	%	0.005	1 5	35.6%	Same
Stability	mg/100 ml	(0.027)	(1.4)	34.1%	Same
Demulsification	minutes	0.109	1 0	21.0%	Same
Ash	%	0.000	0.9	17.1%	Same
Distillation, residue & loss	%	0.017	0.9	15.4%	Same
Distillation, FBP	deg F	(0.143)	(0.6)	7.4%	Same
Acid number	mg KOH/mg	0.001	0.4	4.0%	Same

TABLE A-8

COMMERCIAL DIESEL FUEL REGRESSION RESULTS

(Premium fuels)

Property (dependent variable)	Units	Marginal change per year (slope)	T-Statistic of slope	Correlation with time (R^2)	Better, worse, or same
City Bus type					
Significant change:					
Cetane number	no.	(0.345)	(5 9)	75.9%	Worse
Aniline point	deg F	(0.344)	(5 2)	70.9%	Worse
Distillation, IBP	deg F	0.488	2.9	43.1%	Worse
Sulfur content	% wt	0.002	2.0	26.5%	Worse
Insignificant change:					
Viscosity	Cst	0.006	1.4	14.8%	Same
API gravity	deg API	(0.032)	(1.2)	11.5%	Same
Distillation, 50%	deg F	(0.316)	(1.1)	10.4%	Same
Carbon residue	% wt	0.000	0.9	7 4%	Same
Distillation, 90%	deg F	(0.281)	(0.08)	5.7%	Same
Ash	% wt	0.000	(0.4)	1.2%	Same
Distillation, 10%	deg F	0.067	0.3	1 1%	Same
Distillation, FBP	deg F	0.051	0.1	0.1%	Same
1-D					
Significant change:					
Flash	deg F	(1.000)	(3.3)	78.1%	Worse
Aniline point	deg F	(0.500)	(2.6)	70.0%	Worse
Sulfur content	% wt	0.004	2.1	46.0%	Worse
Insignificant change:					
Viscosity	cSt	(0.011)	(1.8)	39.0%	Same
Distillation, 10%	deg F	(0.821)	(1.7)	35.4%	Same
Carbon residue	% wt	0 002	1 5	42.0%	Same
Cetane number	no	0 250	1 2	21.3%	Same
Distillation, FBP	deg F	(0 464)	(0.7)	9 8%	Same
Distillation, IBP	deg F	0 700	0.7	14.8%	Same
Ash	% wt	(0.000)	(0.7)	12 5%	Same
Distillation, 50%	deg F	(0 300)	(0.3)	3 4%	Same
Distillation, 90%	deg F	(0 143)	(0.3)	1 4%	Same
API gravity	deg API	0 020	0 2	1 1%	Same
Cetane number	Index	0 010	0 1	0 6%	Same

COMMERCIAL DIESEL FUEL REGRESSION RESULTS

(Regular fuels)

Property (dependent variable)	Units	Marginal change per year (slope)	T-Statistic of slope	Correlation with time (R^2)	Better, worse, or same
Truck-Tractor type					
Significant change:					
Aniline point	deg F	(0.253)	(7 5)	83.8	Worse
Cetane number	no	(0.322)	(6 7)	80 5	Worse
Distillation, FBP	deg F	0 980	4 2	61 1	Worse
Distillation, 90%	deg F	0 537	2.9	44 1	Worse
Ash	% wt	0.000	2.9	43.2	Worse
API gravity	deg API	(0 053)	(2.6)	37 2	Worse
Distillation, IBP	deg f	0.362	2.4	33 7	Worse
Insignificant change:					
Sulfur content	% wt	0.001	1 5	17.5	Same
Carbon residue	% wt	0.001	1 3	12.9	Same
Viscosity	cSt	0.002	0.7	3 8	Same
Distillation, 10%	deg F	0.056	0 4	1 5	Same
Distillation, 50%	deg F	(0.066)	(0.4)	1.3	Same
2-D					
Insignificant change:					
Distillation, 90%	deg F	1 679	1 8	38.9	Same
Viscosity	cSt	0.027	1 6	32.6	Same
Distillation, 50%	deg F	2.000	1 5	41 7	Same
Aniline point	deg F	0.580	1 5	41 4	Same
Distillation, FBP	deg F	1 821	1 4	29 0	Same
Flash	deg F	(0 600)	(1 2)	32 1	Same
Cetane index	index	0 140	0 8	16 0	Same
Distillation, 10%	deg F	0.321	0 6	6.9	Same
Carbon residue	% wt	0.004	0 6	10 1	Same
Cetane number	no	0.068	0 5	4 6	Same
API gravity	deg API	(0.070)	(0 4)	4 6	Same
Sulfur content	% wt	(0.001)	(0 3)	1 8	Same
Distillation, IBP	deg F	0.100	0.1	0 1	Same
Ash	% wt	0.000	0 0	0 0	Same

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[A-2] Shelton, E.M. and C.L. Dickson. *Aviation Turbine Fuels, 1984.* National Institute for Petroleum and Energy Research, Bartlesville, OK, Mar 1985.

[A-3] Ricciardelli, J. *Physical and Chemical Properties of JP-5 Fuel. 1980 – 1983.* Naval Air Propulsion Center, Trenton, NJ, Dec 1984; and L. Grabel. *Physical and Chemical Properties of JP-5 Fuel, 1977 – 1980.* Naval Air Propulsion Center, Trenton, NJ, Jan 1982.

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APPENDIX B

CONVERSION CAPACITY AND CRUDE OIL QUALITY

In this appendix, we examine the hypothesis proposed in Chapter 4 that the quality of crude oil imported into the United States changes in response to the amount of conversion capacity available. As U.S. refiners invest in more (or less) conversion capacity, they buy more (or fewer) heavy crude oils in order to profit from their investments. The evidence that we present below strongly supports this hypothesis, even though the data on crude oil quality is sparse.

Researchers at the National Institute for Petroleum and Energy Research (NIPER) have estimated crude oil quality trends over the 8-year period 1978 to 1985 by drawing together data from several sources [B-1]. Although the data are not consistent they show similar trends.

To test our hypothesis, we used the ordinary least-squares regression technique to determine whether the correlation between conversion capacity and API gravity is statistically significant.

We estimated an equation of the form:

$$\text{API Gravity} = C + [B\,(\text{Capacity})] + [D\,(\text{Capacity})^2] + E$$

where:

C = a constant, or intercept,

B and D = coefficients that estimate the marginal change in API gravity per unit change in conversion capacity

E = an error term to measure the unexplained variation.

We found that the percentage of catalytic cracking capacity correlated very strongly with the API gravity of imported crude oil since it accounted for about 90 percent of the variation in imported crude oil gravity between 1978 and 1985.

Using least-squares regression, we obtained the following values for our equation:[1]

C = 260.08

B = –14.21

D = 0.22

(Capacity = Percent catalytic cracking capacity)

The "T-statistics" of the constant and of both coefficients exceed 2.0, indicating a good probability (greater than 0.95) that the numbers are significant (i.e., non-zero).

Figure B-1 compares the "fitted line" from our equation with the actual data points - the API gravity of imported crude oil - to show how well the equation results fit the actual data. Figure B-2 uses the equation to estimate the gravity of imported crude oils during the period 1970 to 1987 and also includes the actual values between 1978 and 1985. The figure indicates that the crude oil quality decline from 1978 through 1985 was not part of a longer-term decline; i.e., future capacity trends imply that crude oils may not get worse.

While the regression results strongly support our hypothesis, six data points are not enough to give us complete confidence in the results (1979 and 1981 are missing). In addition, the regression by itself does not indicate the direction of causality. However, it is more plausible that imported crude oil gravity responds to conversion capacity than vice-versa since the leadtimes involved in building capacity are longer than those involved in purchasing crude oil.

The evidence strongly supports the hypothesis that U.S. refiners increased their imports of heavy crude oils to fill their available conversion capacity. The implication, as shown in Figure B-2, is that crude oil quality should level off as conversion capacity levels off. That is, we cannot reliably predict future crude oil quality by a straight-line extrapolation of past trends; crude oil quality is not headed inexorably downward.

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[1]By including hydrocracking in addition to catalytic cracking in our equation, we could explain essentially all – 99 percent – of the variation between conversion capacity and imported crude oil quality. We have used the equation above, however, because it is simpler to plot and present and appears to give better predictions outside the range of the existing data.
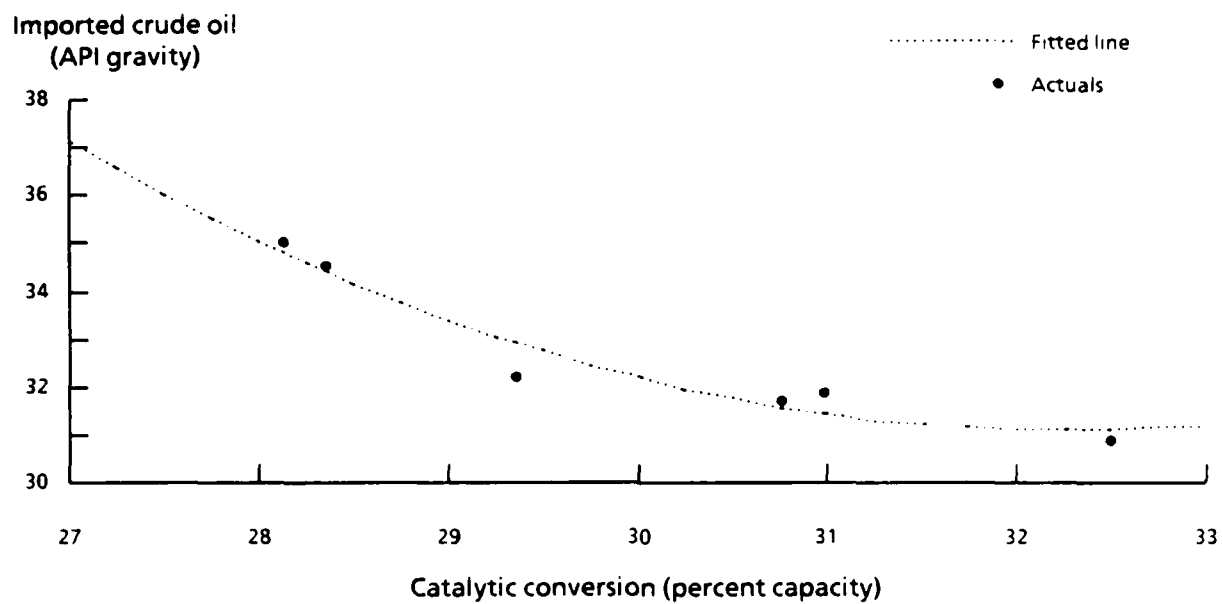
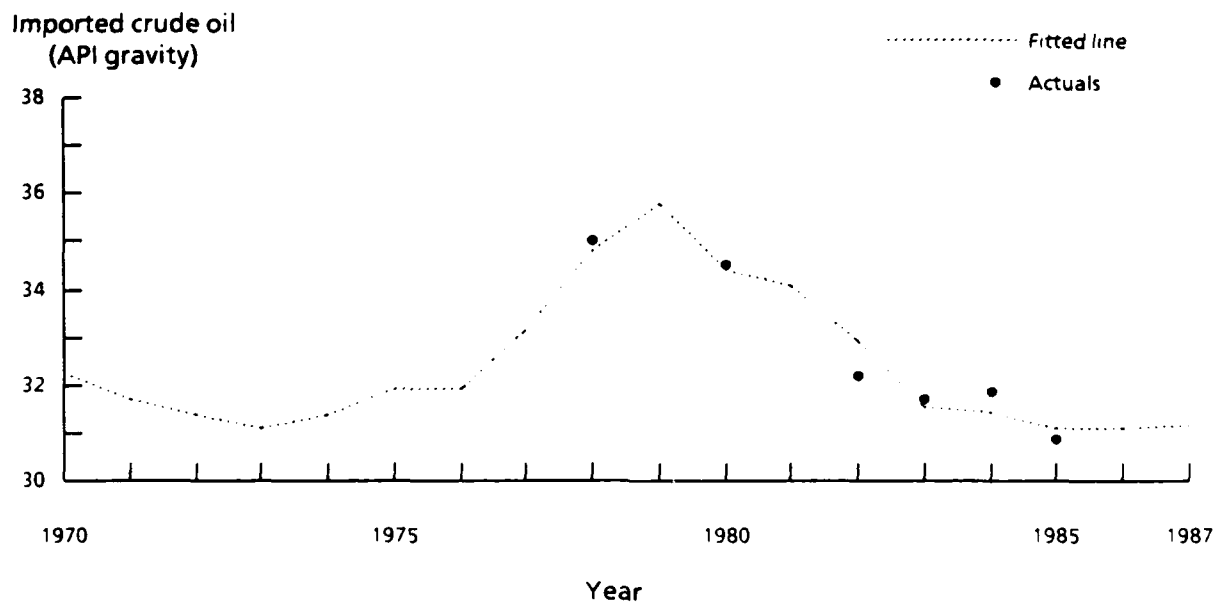**FIG. B-1. CONVERSION CAPACITY VERSUS CRUDE OIL GRAVITY**

FIG. B-2. CRUDE OIL GRAVITY TRENDS

REFERENCE

[B-1]   Wells, J.W. and R.P. Anderson. *Trends in Refinery Feedstock Properties and Refining Problems.* National Institute for Petroleum and Energy Research, Bartlesville, OK, Sep 1986.

APPENDIX C

FUEL STABILITY CONFERENCE FINDINGS

The 2nd International Conference on Long-Term Storage Stabilities of Liquid Fuels was held in July/August 1986. Because the conference papers and discussion represent the latest research in fuel storage stability and related areas, we reproduce the overall findings of the conference below [C-1].

The conference findings are fairly technical. Nevertheless, the basic points support (and, indeed, contributed to) our own findings. In particular:

- Jet fuel storage stability is satisfactory.

- Diesel fuel storage stability depends largely on the extent of refinery conversion.

- Accelerated storage stability tests are not dependable.

The conference findings are (italics added):

OVERALL OBSERVATIONS

- *In general, jet fuel long-term storage stability appears satisfactory.* Heavily hydrotreated stocks require the addition of oxidation inhibitors, primarily hindered phenols, to prevent peroxide formation.

- *The storage stability of middle distillates,* such as gas oils, diesel fuels, and heating oils, *depends upon the amount and type of cracked stocks included.* Amine-type stabilizers, as opposed to primary amine-type antioxidants, appear most successful in preventing sediment formation, but the selection of additives still seems to be pragmatic and empirical rather than based on theory.

- Although sediment weight is used by most as a criterion of fuel suitability, several investigators emphasized the lack of correlation between sediment weight and fuel filtration characteristics. The ability of particles to settle or to stay suspended as a function of particle size appears to be a major factor. Several laboratory filtration tests are under development.

- The need for a short-term test for the prediction of storage stability continues, but *no test which accelerates conditions by increasing test temperature is dependable over a wide range of fuels.* In this

connection, several investigations using oxidation accelerators at lower temperatures appear worthy of further study.

- Microorganisms can cause storage difficulties, particularly in wet caverns. However, available biocides can control the problems, except in wet cavern storage. Some biocides were reported to be effective at low parts per million concentration in fuels.

- Several new, useful procedures are available to detect the onset of fuel corrosivity by more sensitive techniques than the standard corrosion tests.

- A new device for measuring lacquer-type deposits on thermal oxidative test tubes (ASTM D 3241) uses the principal of dielectric breakdown voltage. This method offers to be most useful in fuel thermal stability programs looking at neat and storage changes as well as additive and metallurgical effects on deposit kinetics.

- New techniques utilizing mass spectroscopy and supercritical liquid chromatography are helping to understand the mechanism of sediment formation in middle distillate fuels.

REFERENCE

[C-1] *Conference Proceedings: 2nd International Conference on Long-Term Storage Stabilities of Liquid Fuels.* L.L. Stavinoha, Ed., Southwest Research Institute, San Antonio, TX, Oct 1986, pp. 13 – 14.

APPENDIX D
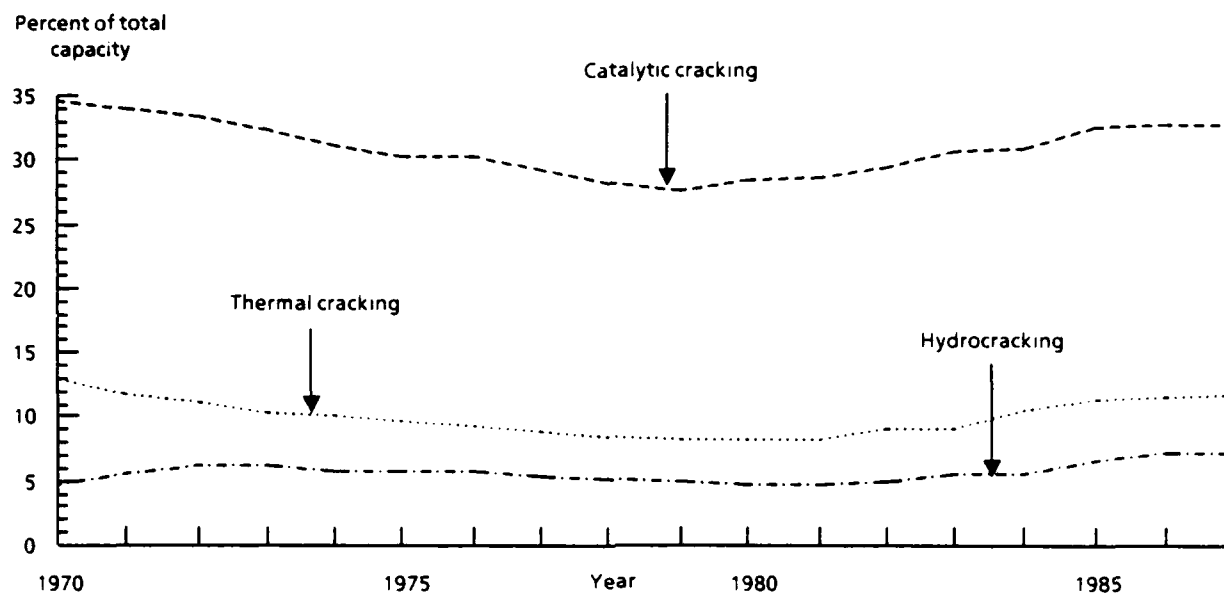
MEASURES OF REFINERY COMPLEXITY

This appendix supplements the analysis of past trends in the U.S. refining industry presented in Chapter 4. That analysis looked at post-1970 trends in conversion capacity and in the utilization of that capacity. This appendix introduces another way to assess refinery trends — the Nelson refinery complexity index — and shows how that index also supports the conclusion in Chapter 4 that available evidence on refinery trends does not point to a worsening fuel quality problem. The Nelson refinery complexity index gives a rough measure of changes in refinery equipment costs based on equipment complexity [D-1].
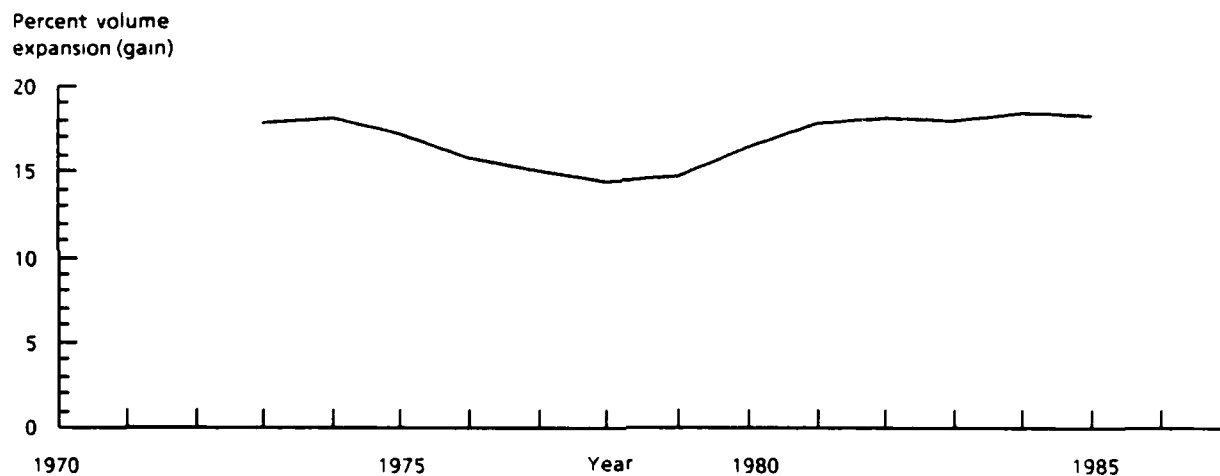
Figure D-1 displays three measures of U.S. refining trends. Two of the measures [Figures D-1(a) and (b)] were introduced in Chapter 4; they show that refinery conversion has increased since the beginning of the decade; the third measure [Figure D-1(c)] shows that refining complexity has increased over the same period. All three measures also show that most of these increases mark a return to conversion and complexity levels characteristic of the early 1970s. Thus, these measures support the view that a fuel quality problem is unlikely to emerge as the result of newly more intensive processing of crude oil. Conversion and complexity have increased, but these trends do not mark a dramatic increase over anything the industry had previously experienced.

The Nelson complexity index has several drawbacks as a measure of the potential impact of refinery changes on product quality. First, the index reflects increases in refinery processes designed to improve product quality (by boosting gasoline octane and by lowering sulfur content) as well as conversion processes that may reduce product quality. Second, the Nelson complexity factors approximate relative construction costs for the major refinery processes, not processing capacity or severity. Third, hydrocracking, which is the conversion process with the least harmful effect on product quality, has the largest effect on the index. To eliminate the first drawback we also show a "modified Nelson index" in Figure D-1(c) that reflects changes in refinery conversion processes only. The modified index reveals

(a) Conversion capacity

Percent of total capacity

Catalytic cracking

Thermal cracking

Hydrocracking

1970   1975   Year   1980   1985

(b) Utilization of conversion capacity

Percent volume expansion (gain)

1970   1975   Year   1980   1985

(c) Nelson Complexity Index

Nelson Index

Modified Nelson Index

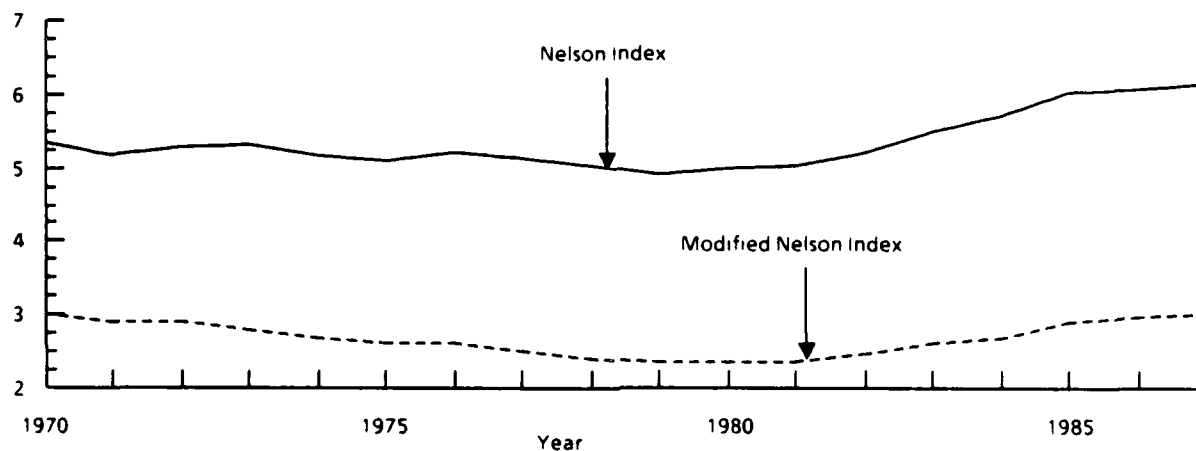1970   1975   Year   1980   1985

FIG. D-1. U.S. REFINING TRENDS

that conversion complexity in 1987 – as measured by the Nelson factors – is below the 1970 complexity level.

The complexity indices shown in Figure D-1(c) are the sum of the products of two sets of numbers. One set represents the capacity of particular refining processes as a fraction of total refining capacity. (For example, this set includes the figure of 0.284 for catalytic cracking in 1980 because the capacity to perform that process was nearly one-third of total refining capacity in that year.) The other set represents the "complexity" of each of those refining processes as estimated by W. L. Nelson, whose various refining indices are published by *Oil and Gas Journal*. (Nelson bases his complexity estimates on the cost of building different kinds of processing capacity. For example, he awards a "1" to vacuum distillation capacity because it is simple and relatively cheap to build and a "10" to a unit of complex and relatively costly hydrocracking capacity.)

Table D-1 illustrates how such number sets were used to obtain the year-by-year indices of refining complexity used in constructing Figure D-1. Column A lists the six refinery process categories adapted to provide a comparable basis for multiplying capacity fractions and complexity factors. (Available data on process capacity is organized under somewhat different headings than those used by Nelson in computing his complexity factors; categories under Column A permit multiplication of comparable numbers despite such differences.) Column B lists the ratio of 1980 vacuum distillation capacity to total 1980 refining capacity, and so on. Column C lists Nelson complexity factors.[1] The first six figures in Column D are the extensions of capacity fractions and complexity factors; their sum is 4.969, the complexity index figure that was also used to graph the Nelson complexity index in Figure D-1(c). Column E lists the same numbers as in Column D for conversion processes only; their sum gives the modified Nelson index that is also shown in Figure D-1(c).

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[1]In some cases Column C figures reflect adaptation of more detailed Nelson factors. For example, Nelson's "Thermal Processing" category includes not only Gas Oil Cracking and Visbreaking, with complexity factors of 3 for each, but also Fluid Coking and Delayed Coking, with factors of 5 apiece. The corresponding category in Table D-1, Thermal Operations, splits the difference with a factor of 4.

TABLE D-1

ILLUSTRATIVE CALCULATION OF THE NELSON COMPLEXITY INDEX

A	B	C	D	E
Refining process	Fraction of total 1980 refining capacity	Nelson complexity factors	Intermediate products (B x C)	Intermediate products (B x C)
Vacuum distillation	0.357	1.000	0.357	--
Thermal cracking	0.083	4.000	0.333	0.333
Catalytic cracking	0.284	5.500	1.560	1.560
Catalytic reforming[a]	0.210	4.000	0.840	--
Hydrocracking	0.047	10.000	0.475	0.475
Hydrotreating[b] and hydroforming[a]	0.444	3.167	1.404	--
Nelson complexity index for U.S. refineries in 1980:			4.969	
Modified Nelson index (conversion only) in 1980:				2.368

[a] Gasoline quality-improvement process.

[b] Sulfur-removal process.

REFERENCE

[D-1] *Refinery Complexity, Volume II.* The National Petroleum Council, Dec 1979: pp. C9—C10.

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